



# 2007 Enceladus Flagship Study



**John Spencer**  
**Southwest Research Institute**

**Planetary Decadal Survey**  
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**Goddard Study Lead: Andrea I. Razzaghi**  
**Science Co-Chairs: Amy Simon-Miller, John Spencer**  
**Mission Systems Engineer: Dave Di Pietro**  
**Instrument Systems Engineer: Gary Sneiderman**  
**Mission Operations: Steve Tompkins**  
**Flight Dynamics: Dave Quinn**  
**Technology Lead: Vince Bly**  
**Financial Analyst: Lauri Via**



# Science Definition Team

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## Team Leaders:

- Amy Simon-Miller, John Spencer

## Remote Sensing:

- Bonnie Buratti, Brad Dalton, Paul Helfenstein

## Geophysics:

- Amy Barr, Andrew Dombard, Francis Nimmo

## In Situ Analysis:

- Will Brinkerhoff, Danny Glavin, Joe Kirschvink, Don Mitchell



# Study Approach



- Definition of science goals
- Risk Reduction/Fact Finding Studies
  - E.g., dust shielding, solar electric propulsion design
- Three focused mission concept designs in the GSFC Integrated Mission Design Center (IMDC)
  - Use knowledge gained in each IMDC run to determine next steps
- Decided to remain in Phase I (i.e. no single highly-developed point design)
  - Large trade space and numerous architecture options required evaluation
- Public version of final report is available at [http://www.lpi.usra.edu/opag/Enceladus\\_Public\\_Report.pdf](http://www.lpi.usra.edu/opag/Enceladus_Public_Report.pdf)

# The Scientific Importance of Enceladus

*"Enceladus is arguably the place ... where exploration is most likely to find a demonstrably habitable environment"*

2009 Decadal Survey White Paper

- One of the most plausible locations for extraterrestrial life in the solar system
- Direct samples from the potentially habitable zone are readily accessible
  - Our best opportunity to sample the interior of an icy satellite, regardless of habitability
- Currently active tectonism and cryovolcanism illuminates geological processes important throughout the outer solar system
- The dominant source of dust, neutral gas, and heavy ions in the Saturn system



# One of the Most Plausible Locations for Extraterrestrial Life



## Requirements for life:

1. Liquid water
  - ? Plausible but unproven on Enceladus
2. Organic chemistry
  - ✓ Strong evidence from plume composition
3. Energy source
  - ✓ High observed temperatures and evidence for direct surface/interior interchange
  - ✓ Redeposition of oxidant-enriched E-ring particles may provide additional chemical energy (Parkinson et al. 2007)



# Ease of Sampling



- Fresh samples from the interior are accessible by simply flying through the plume
- Biological implications:
  - Habitability of the source region can be addressed *directly*
  - Even the presence of extant life can be addressed
- Unique geochemical information about icy satellite interior processes is available, regardless of habitability

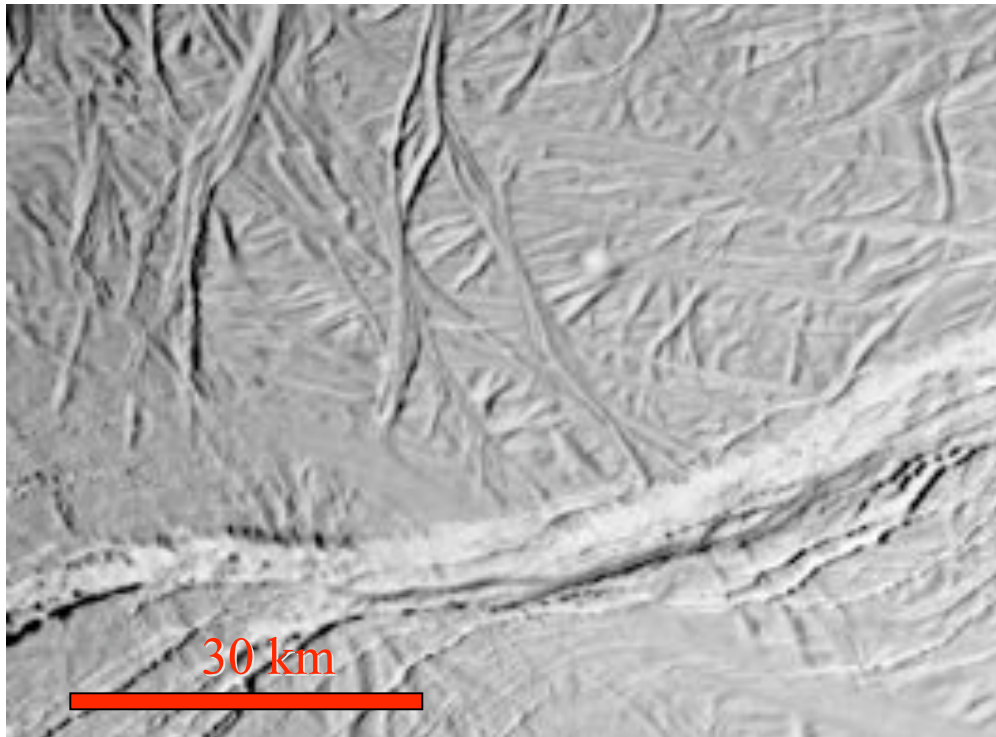




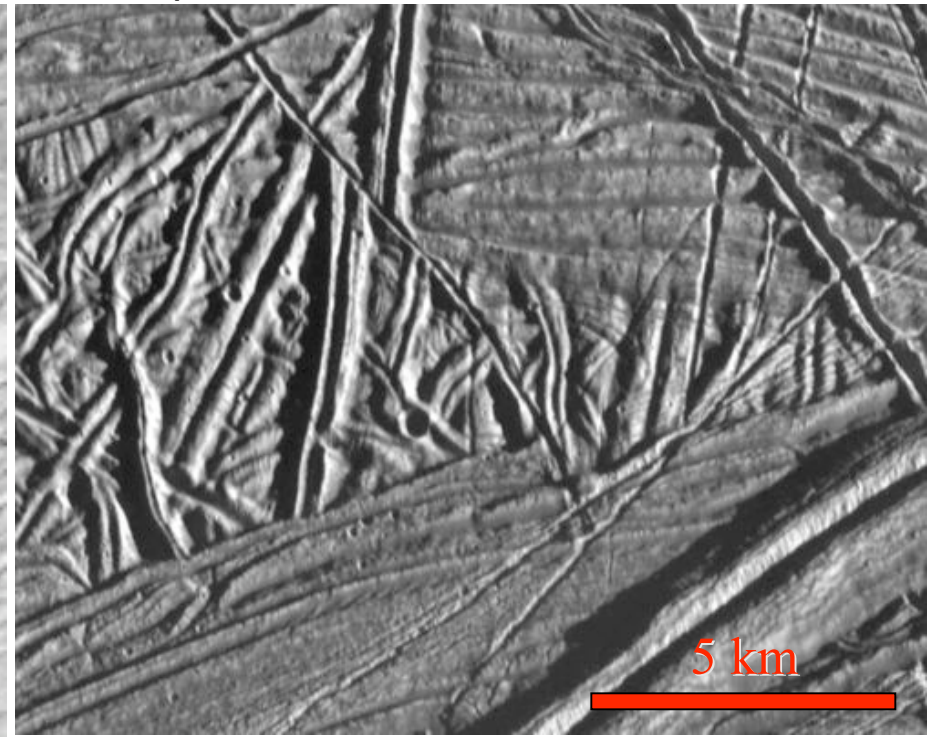
# A Key to Understanding Other Icy Satellites



Enceladus



Europa



- “The present is the key to the past”
  - Enceladus illuminates *all* icy satellites by providing presently active examples of processes that have happened in the past on other icy satellites (Europa, Ganymede, Dione, Miranda, Ariel, Triton...)



# Prioritized Science Goals



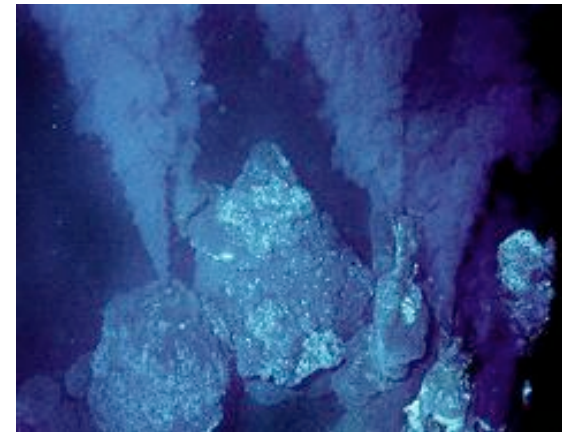
1. Highest-Priority Goal
  - Biological Potential
2. Second-Level Goals
  - Composition
  - Cryovolcanism
  - Tectonics
  - Tidal Heating and Interior Structure
3. Third-Level Goals
  - Saturn System Interaction
  - Surface Processes



# Level 1 Science Goal: Biological Potential



- Is liquid water present?
  - How extensive is it?
  - Is it long-lived?
- What is its chemistry?
  - Inorganic?
  - Organic?
- What energy sources are available for life?
- Is life present now?

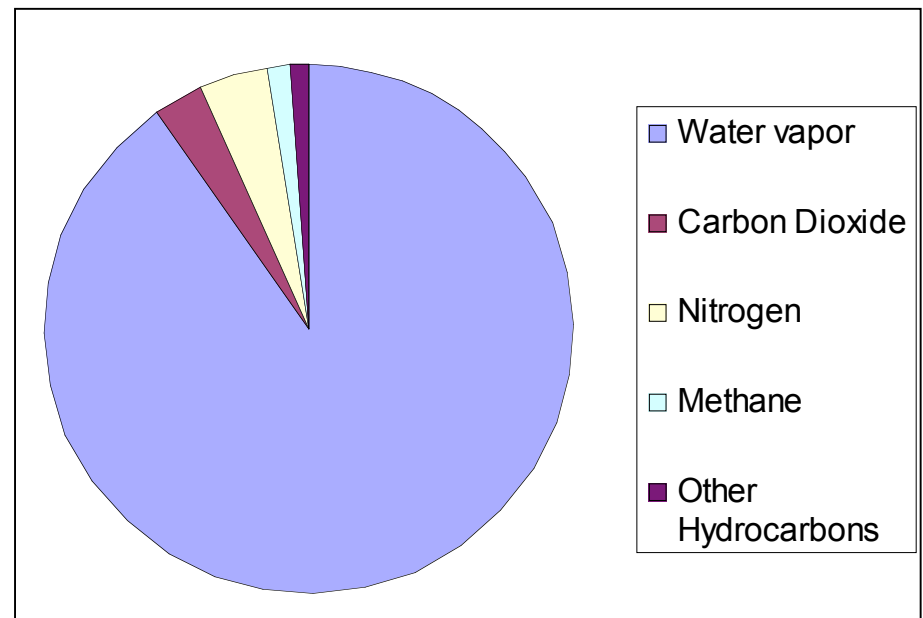




# Level 2 Goal: Composition



- What is the interior composition?
  - Are clathrates important?
  - Is ammonia important?
  - Organic inventory?
  - Silicate composition?
  - Redox state / disequilibrium chemistry
- What is the surface composition?



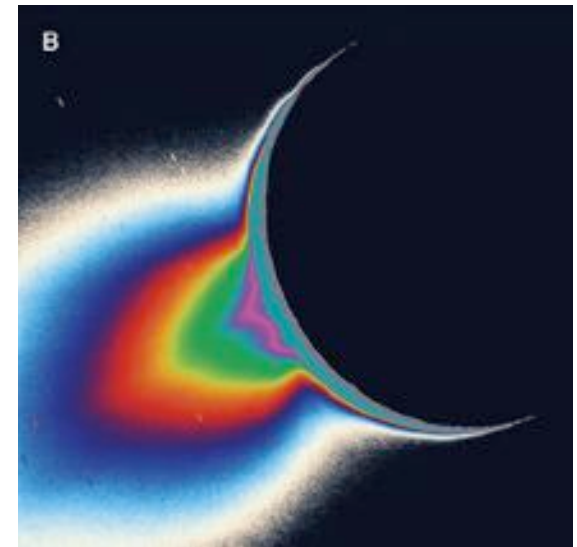
Enceladus plume composition



# Level 2 Goal: Cryovolcanism



- What is the nature of the plume source?
  - Are liquids involved, and how close to the surface?
  - How is energy supplied to the plumes?
- What are the resurfacing rates?
  - Due to particles?
  - Due to gas?
  - Spatial distribution?
- What are the escape rates?
  - Due to particles and what is the size distribution?
  - Due to gas
  - Role of mass loss in long-term chemical and physical evolution
- Is there activity away from the south polar region?
- Is there extrusive or intrusive cryovolcanic activity?

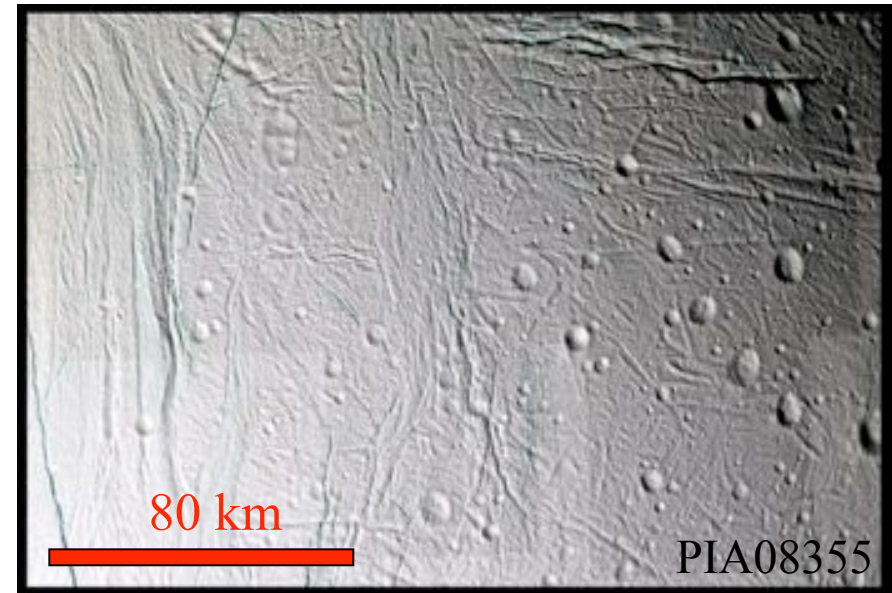




# Level 2 Goal: Tectonics



- What drives the extensive tectonic activity?
  - Convection?
  - “Plate tectonics”?
  - Polar wander?
  - Changes in rotation rate?
  - Tidal stresses?
- What tectonic features result from extension, contraction, or shear?
- Why does the intensity of tectonism vary so widely across the surface?
- How has tectonism varied through time?
- What can Enceladus tell us about tectonic processes on other icy satellites?

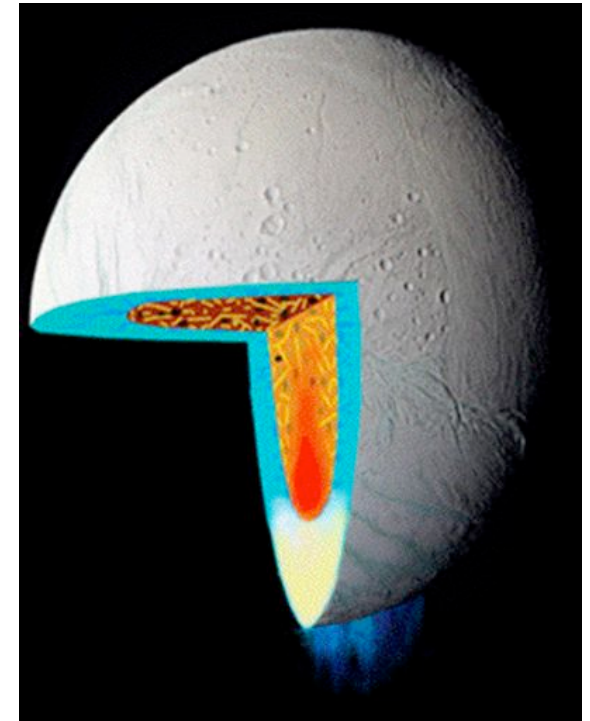




# Level 2 Goal: Tidal Heating and Interior Structure



- Tidal Heating
  - Dissipation mechanism
    - Dissipation site
    - Total power
  - Spatial distribution
  - Variability over long timescales
    - How did it get started?
    - Has it been continuous?
- Interior Structure
  - Thermal structure
  - Degree of differentiation
  - How big is the core?
  - How thick is the lithosphere?
  - Is there an ocean? Volume?
  - Are there more isolated liquid water bodies?
  - Is there an intrinsic magnetic field?

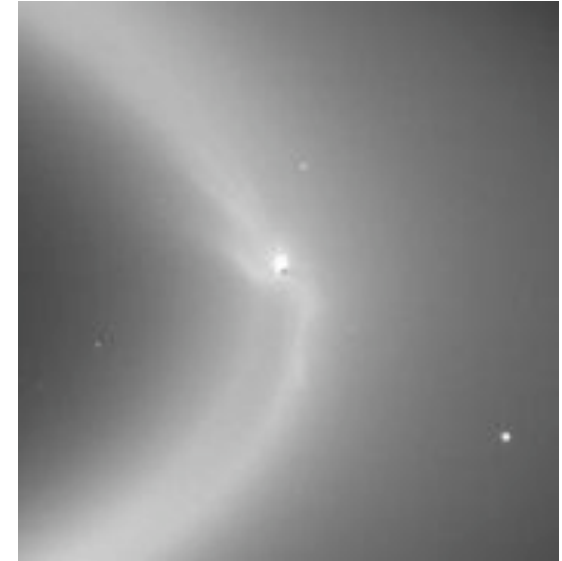




# Level 3 Goal: Saturn System Interaction



- E-ring
  - Dust grain dynamics?
    - Gravitational vs EM forces
  - Loss processes, ring lifetime.
- Neutral torus
  - Variability
  - Loss Processes
- Magnetospheric plasma
  - Enceladus sources
  - Charge exchange
  - Coulomb collisions
  - Dust collisions
- Role of Enceladus as a radiation shield
  - Can Enceladus-like worlds in extrasolar satellite systems enhance (or degrade) habitability of neighboring moons by damping magnetospheric radiation?





# Level 3 Goal: Surface Processes



- Is photolytic or radiolytic surface chemistry important? Does it affect the interior chemistry?
- Does sputtering or micrometeorite gardening contribute significantly to escape of material from Enceladus?
- Relative importance of exogenic vs. endogenic processes
- Mass wasting, seismic shaking?
- Nature of surface / interior exchange

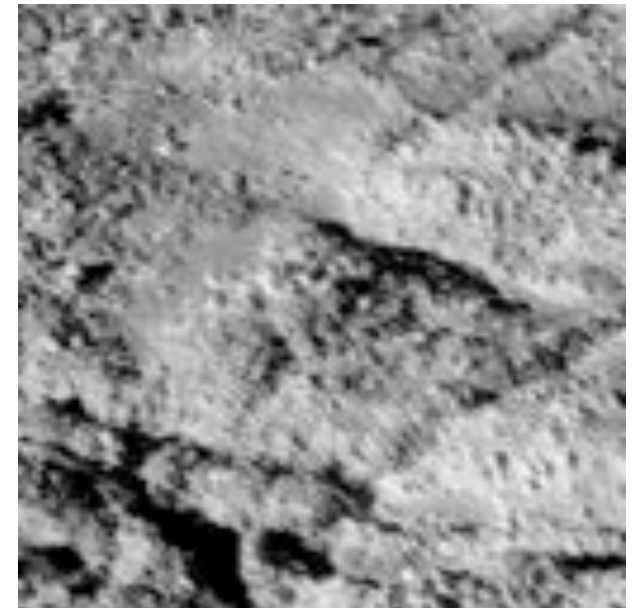


Image width:  
2 km



# Strong Relationship to 2002 Decadal Survey Goals



These science goals are highly relevant to most of the major goals set by the Decadal Survey:

	Biological Potential	Tidal heating & Internal Structure	Composition	Cryo-volcanism	Tectonics	Surface Processes	Saturn System Interaction
<b>The First Billion Years of Solar System History</b>							
1. Initial processes		X	X				
<b>Volatiles and Organics: The Stuff of Life</b>							
4. History of volatiles	X	X	X	X		X	
5. Nature and evolution of organics	X		X			X	
6. Mechanisms of volatile evolution	X	X		X	X	X	X
<b>The Origin and Evolution of Habitable Worlds</b>							
7. Processes responsible for habitability	X	X		X	X	X	X
8. Life beyond Earth?	X	X		X	X		
<b>Processes: How Planetary Systems Work</b>							
11. Contemporary processes		X		X	X	X	X



# Measurement Objectives



- Full traceability matrix generated...

Science Objective	Measurement Objective(s)	Measurement Requirement	Mission Requirement	Suggested Instrument	Mission Type	Priority
	Location and distribution of liquid water	Magnetic field measurements to 0.1 nT	Polar Orbits ideal	Magnetometer	Saturn or Enceladus Orbiter	1
		Surface magnetic field measurements to 0.1 nT	Lifetime of several Enceladus days, continuous operation.	Magnetometer	Hard or Soft Lander	2
		h <sub>2</sub> to 0.1; tidal displacements to 1 m; Altimetric profiles with resolutions 10 m (horizontal) and 0.1 m (vertical)	Enceladus orbital knowledge to 10-m precision; also possible with multiple (~10) flybys with range <1000 km. Simultaneous altimetric and gravity observations help. Desire 10-m spot size; laser ranges to 1000 km; multibeam for crossover analysis (require	Laser Altimeter	Saturn or Enceladus Orbiter	1
			Determine range to 1-2 transponders; for single transponder, orbital knowledge to 1-m precision required. Lifetime of several Enceladus days required.	Transponder, part of comm. System	Hard or Soft Lander	1
		k <sub>2</sub> to 0.01; Degree-2 gravity coefficients to 1 part in 10 <sup>3</sup> . Lower priority: Gravity profiles to 1 mgal at surface, with 5-10 degree (~20-40 km) resolution	Multiple flybys w/ simultaneous altimetric and gravity measurements. Orbiter w/ both polar and equatorial passes.	USO, part of comm. System	Saturn or Enceladus Orbiter	1
	Seismic measurements with long period sensitivity better than 1mm at periods 0.001-0.1 Hz. Short period sensitivity better than 0.1 micron/s at frequencies up to 100 Hz	Lifetime of several Enceladus days. One location is sufficient for normal mode measurement of shell thickness, two at different locations are preferred for more detailed interior structure determination	Seismometer	Hard or Soft Lander	1	
	Physical conditions in the active regions	South polar surface temperature maps, spatial resolution ~100m, temperature sensitivity 0.5 K at 60 K	High inclination Enceladus orbits for polar passes, or multiple south polar flybys	Thermal IR Mapper	Saturn or Enceladus Orbiter	1
		South polar daytime imaging coverage, 4 wavelengths (0.35, 0.56, 0.8 1.0 microns), 10 meter resolution. Plume imaging at phase angles from 130 to 175 degrees with spatial resolution of 100 meters. Lower priority: Local stereo topography with 30 m (horiz	High inclination Enceladus orbits for polar passes, or multiple south polar flybys. Variable altitude for very-high-resolution (2 m/pix) imaging of selected areas. Subsolar latitude < -10 degrees during at least some of the prime mission, for south pole	Visible Camera	Saturn or Enceladus Orbiter	1
		Vent subsurface thermal and physical structure	Image subsurface ice to ~250 K isotherm with vertical resolution ~100 m	Sounding Radar	Saturn or Enceladus Orbiter	2
		South polar daytime coverage, 1 - 5 microns, spectral resolution 0.022 microns	High inclination Enceladus orbits for polar passes, or multiple south polar flybys. Subsolar latitude <	Visible Camera	Saturn or Enceladus Orbiter	1



# Measurement Objectives

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- Summary of Key Measurements:
  - Characterize the surface with global imaging, topography, compositional, and thermal maps
  - Probe interior structure seismically and/or with sounding radar
  - Probe interior with tidal response, electromagnetic induction signature, and high-order gravity mapping
  - Investigate chemical, pre-biotic, and potential biotic evolution with in situ chemical analysis of plume gases and solids, and surface analysis



# Astrobiology Measurements



- Almost all proposed measurements contribute to the “Biological Potential” goal, but some are particularly relevant
  - High-resolution imaging of plume particles (from Enceladus orbit)
    - E.g., electron microscope / energy-dispersive X-ray
    - Direct imaging of biological structures?
  - Chirality measurements of organics from the lander
    - E.g., micro capillary electrophoresis analyzer with laser induced fluorescence, based on ExoMars Urey payload.
    - Strong evidence for biology, if found
- Other instruments could also identify biological signatures
  - E.g. detailed characterization of organics via:
    - Orbital mass spectroscopy of the plume
    - Laser desorption mass spectroscopy and electrospray ionization time of flight mass spectroscopy on the surface



# Cassini's Ability to Address These Goals



- 22 flybys total, if XXM is funded and executed successfully
- However, due mostly to pointing limitations, only one prime science goal pre flyby (e.g., remote sensing, in situ sampling, gravity)
  - Only three south polar remote sensing flybys between 2009 and 2017

2008/2009 flyby series:

Date	Orbit	Speed, km/s	Altitude, km	Orbit Inclination	Strawman C/A science emphasis
12-Mar-08	61	14.3	50	High	Particles and Fields: plume sampling
11-Aug-08	80	17.7	50	High	S. Pole remote sensing
9-Oct-08	88	17.7	21	High	Particles and Fields: plume sampling
31-Oct-08	91	17.7	196	High	S. pole remote sensing
2-Nov-09	120	7.7	96	Low	P&F plume sampling
21-Nov-09	121	7.7	1560	Low	S. pole remote sensing
28-Apr-10	130	6.5	96	Low	S. pole gravity
18-May-10	131	7	246	Low	Plume solar occultation



# Other Cassini Limitations



- Limited instrumentation
  - Remote sensing instruments not optimized for high-resolution, wide-area coverage from close range
    - Very limited hi-res remote sensing coverage
  - Mass resolution and range of Cassini mass spectrometers prevents identification of complex molecules
    - Limits understanding of organic chemistry
  - No ability to detect biosignatures such as chirality
  - High speed impacts prevent detailed molecular analysis of plume gases
  - Can't image plume particles
  - No ability to measure tidal flexing
  - No subsurface sounding
- No surface science
- Limited temporal sampling



# Mission Configuration Options: Downselect



Configuration	Only	+ Soft Lander	+ Hard Lander(s)	+ Dumb Impactor	+ Plume Sample Return
<b>Saturn Orbiter</b>	Similar to JPL box study, difficult to justify after Cassini, especially for a Flagship mission.	High science return, requires retropropulsion system (2-4 km/s), and reasonable lifetime	Requires retropropulsion system (2-4 km/s), can be used to create seismic network	Useful with seismic network. Cheap option for subsurface probe (for "control" away from the plumes)	High science value, impractical due to large $\Delta v$ required to escape Saturn, unless sample is collected prior to orbit insertion
<b>Enceladus Orbiter</b>	High science value, potential for very-near or surface science late in the mission, requires retropropulsion system (2-4 km/s)	Highest science value, increases mass into orbit	Low free fall velocity from low orbit, can be used to create seismic network	Cheap option for subsurface probe (for "control" away from the plumes), released before entering orbit	High science value, impractical due to large $\Delta v$ required to escape Saturn, unless sample is collected prior to orbit insertion
<b>Single Flyby</b>	Low science value	Requires large retropropulsion system ( $\sim 7$ km/s). Lacks sufficient relay time or requires comm to Earth. Insufficient science without orbital component	Requires large retropropulsion system ( $\sim 7$ km/s), lacks sufficient relay time	Cheap option for subsurface probe (for "control" away from the plumes), modest science value	High risk, high potential science return; major planetary protection and longevity (25+ yrs) issues.
<b>Lander Only</b>	Requires large retropropulsion system ( $\sim 7$ km/s). Lacks sufficient relay time or requires comm to Earth. Insufficient science without orbital component	N/A	Requires large retropropulsion system ( $\sim 6$ km/s) and has no way to return data	Modest science value	High science value, impractical due to large $\Delta v$ required to escape Saturn, unless sample is collected prior to orbit insertion

- Considered science value and likely cost



# Sample Return



## Science drivers for sample return:

- Enceladus provides a unique opportunity to obtain fresh samples from the interior of an icy satellite and return them to Earth by simply flying past
- Earth laboratories allow much more sophisticated analysis than is possible remotely
- Free return trajectory offers low energy (cheap!) method for returning sample, but with a long mission lifetime
- We did not consider sample return missions in any more detail than was done for the JPL \$1B box studies (q.v.), except for some additional trajectory analysis
- Free-return trajectories exist which provide acceptable acquisition speeds for science, but have unacceptably long flight times (>20 years)



# IMDC Studies



- IMDC Study #1 (Saturn-OL)
  - Saturn Orbiter with Soft Lander
  - Priority One Science Instruments
  - Solar Electric Propulsion (SEP)
- IMDC Study #2 (Enceladus-O)
  - Enceladus Orbiter
  - Priority One Science Instruments, option for hard landers
  - Chemical Propulsion
- IMDC Study #3 (Enceladus-OL)
  - Enceladus Orbiter with Soft Lander
  - Priority One Science Instruments
  - Chemical Propulsion



# Mission Concepts: Summary



	Saturn -OL	Enceladus-O	Enceladus -OL
Mission Description	Saturn orbiter w/soft lander	Enceladus orbiter	Enceladus orbiter w/soft lander
Instruments	Orbiter: imagers and <i>in-situ</i> Lander: imager, seismometer, sample analysis	Orbiter: imagers, radar, and <i>in-situ</i>	Orbiter: imagers and <i>in-situ</i> Lander: imager, seismometer, sample analysis
Trajectory (all use Saturn & Titan gravity assists)	Earth gravity assist	VVEES + Rhea gravity assists	VVEES + Rhea & Dione gravity assists
$C_3$ (km <sup>2</sup> /s <sup>2</sup> )	19.2	19.05	19.05
Launch Date	Mar 2018	29 Sep 2018	29 Sep 2018
Nominal Mission Duration (years)	9.5	17.3	18.3
Orbiter Science Ops (years)	1.3	2.4	2.4
Lander Science Ops (days)	5-8	N/A	5-8
Plume passages	12 @ 3.8 km/s	12 @ 0.143 km/s	12 @ 0.143 km/s
Number of Stages	3	2	3
Propulsion Type	25 kW SEP module Dual-mode chemical orbiter Bi-prop lander	Dual-mode chemical booster & orbiter	Dual-mode chemical booster & orbiter Mono-prop lander
$\Delta V$ from Chemical Propellant (m/s)	Orbiter: 2797 Lander: 4315	Booster and orbiter: 4977	Booster and orbiter: 4497 Lander: 415
Launch Mass (kg)	6196	5810	6320
Launch Vehicle Type	Delta IV Heavy	Delta IV Heavy	Delta IV Heavy
Cost (FY07 \$B)	2.6 to 3.0	2.1 to 2.4	2.8 to 3.3



# Saturn-OL Overview



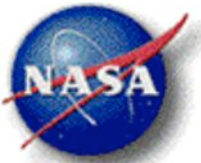
- Saturn Orbiter
  - ~50 Enceladus flybys at 4 km/s (8.22-d orbit)
- Soft Lander
  - Battery powered, ~8-day lifetime
- 3-Stage Spacecraft (Including Lander)
  - SEP used for 1<sup>st</sup> Stage, chemical propulsion used for stages 2 & 3
    - SEP separates at ~3 AU
  - Single Earth flyby
  - $C3 = 19.3 \text{ km}^2/\text{s}^2$
  - Delta IV Heavy launch vehicle



# Saturn Orbiter + Enceladus Lander: Instrument Science Value



Instrument	Mission Element	Included in Strawman Payload?	Biological Potential (Priority 1)	Tidal Heating and Interior Structure (Priority 2)	Composition (Priority 2)	Cryovolcanism (Priority 2)	Tectonics (Priority 2)	Surface Processes (Priority 3)	Saturn System Interaction (Priority 3)
Thermal Mapper	Saturn Orbiter	Y	8	8	2	8	5	2	0
Visible Mapper	Saturn Orbiter	Y	6	7	4	8	8	8	6
NIR Mapper	Saturn Orbiter	Y	7	3	8	5	3	5	5
Laser Altimeter	Saturn Orbiter	Y	7	7	2	5	7	4	0
USO	Saturn Orbiter	Y	7	7	2	4	6	1	0
Mag	Saturn Orbiter	Y	7	6	2	3	2	1	6
LC/GC-MS	Saturn Orbiter	Y	8	3	8	7	2	5	8
Dust Analyzer	Saturn Orbiter	Y	7	3	8	7	2	5	8
Framing Camera	Saturn Orbiter	N	3	5	2	6	5	3	4
UV Spectrometer	Saturn Orbiter	N	3	2	5	6	0	3	7
Radar Sounder	Saturn Orbiter	N	6	7	4	7	6	5	0
Low Energy Plasma Analyzer	Saturn Orbiter	N	2	0	6	5	0	4	9
Energetic Particle Spectrometer	Saturn Orbiter	N	2	0	6	5	0	6	9
Lander Camera (two)	Soft Lander	Y	4	4	5	5	4	8	1
Transponder	Soft Lander	Y	5	5	2	4	5	1	0
Seismometer	Soft Lander	Y	5	9	3	6	8	4	0
Surface Chemistry Package	Soft Lander	Y	9	2	9	6	2	7	7
LDMS	Soft Lander	Y	9	0	8	5	0	7	7
Surface Ice Oxidant Detector	Soft Lander	Y	8	0	7	5	0	7	7
Tunable Laser Spectrometer	Soft Lander	N	7	0	6	4	0	6	5
Penetrator Camera	Hard Lander	N	4	4	5	5	4	8	1
Transponder	Hard Lander	N	5	5	2	4	5	1	0
Seismometer	Hard Lander	N	5	9	3	6	8	4	0



# Saturn-OL: Science Trades



- Saturn orbiter requires high-speed plume passages ( $> 4$  km/sec)
  - Difficult to capture intact dust and molecular samples for detailed analysis: limits plume science
- In compensation, lander chemistry package allows detailed chemical analysis of plume fallout on the surface, complements orbital plume analysis
  - Large samples available to lander: sensitive to trace species
- Saturn orbit limits quality of geophysical data
  - We expect to be able to determine Love numbers and perhaps EM induction signature, but details are TBD
- In compensation, lander seismometry package complements orbital geophysical data
  - Probes thickness and structure of lithosphere



# Saturn-OL Science



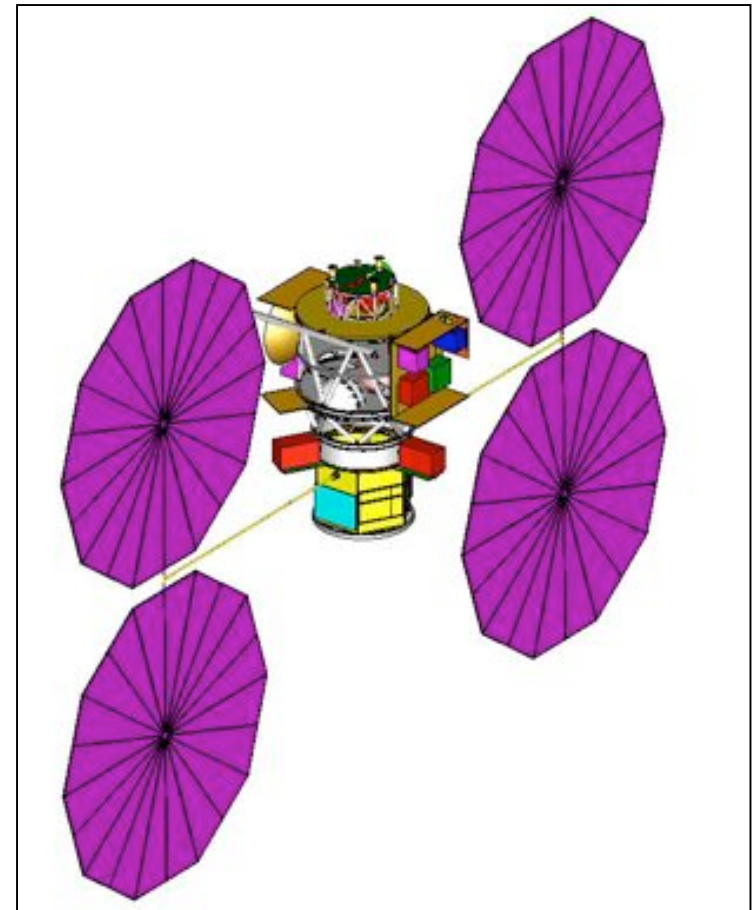
- Orbiter Science Drivers:
  - Global mapping: visible, near-IR and thermal IR
    - Understand tectonics, cryovolcanism, surface processes
  - Determine Love numbers w/ laser altimetry and Doppler tracking
    - Constrain interior structure, and presence or absence of a global ocean
  - In situ analysis of plume gas and dust components
    - Understand cryovolcanic processes, organic chemistry
- Lander Science Drivers:
  - Detailed in situ analysis of surface chemistry (esp. organic)
    - Composition, cryovolcanism, habitability, presence of key amino acids and biotic compounds?
  - High-frequency and low-frequency seismometry
    - Ice shell thickness, structure, cryovolcanism
  - Imaging
    - Surface processes



# Saturn-OL: Results

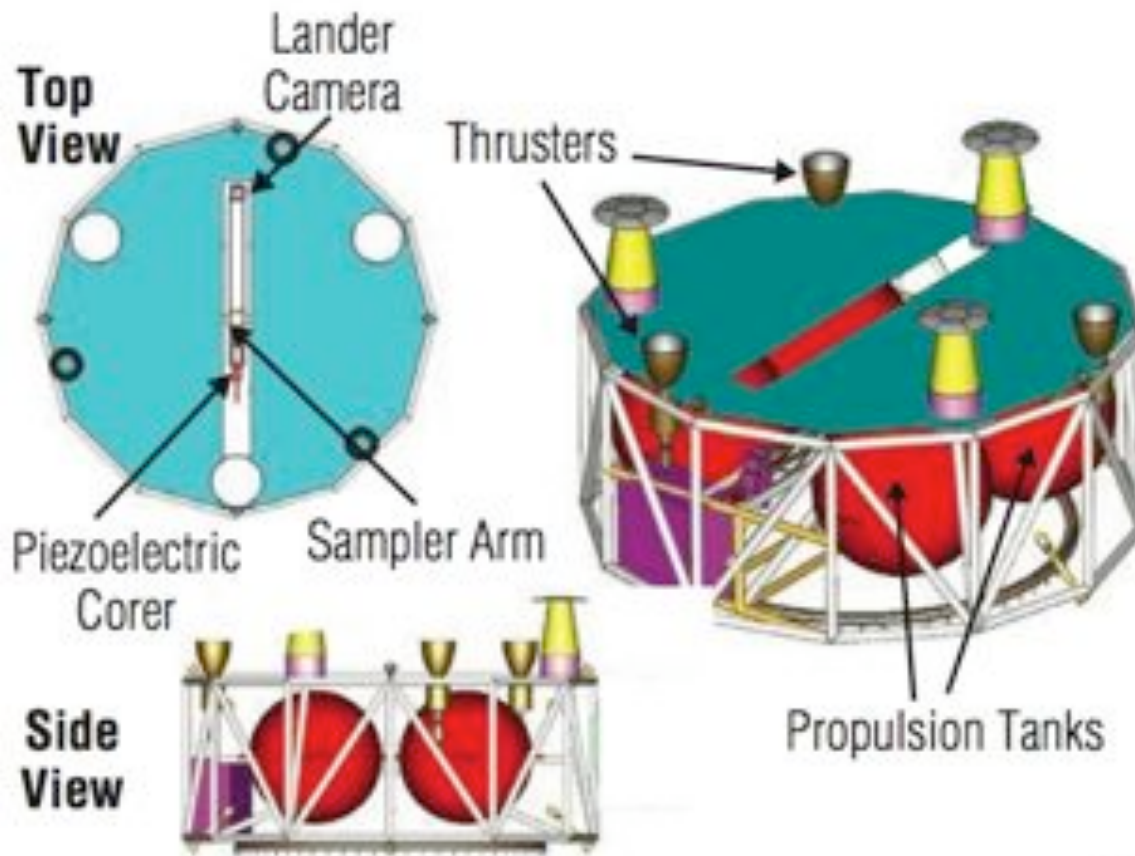


- 6500 kg can be launched
- Total mission lifetime ~ 9.5 yr
  - 7.5-yr trip time to Saturn
  - 8.2-day orbit achieved at L+8.25 yr
    - 9 months for post SOI Titan flybys
- ~ 6200 kg gross mass (wet)
  - ~ 5% launch margin
  - 80 kg science payload on orbiter
  - ~ 870 kg lander (wet mass)
    - ~20 kg science payload on lander
- Mission appears feasible
  - 30% reserve held on mass, power, data volume
  - Subsystems, trajectory and payloads can be optimized





# Saturn-OL Lander Design



EN043



# Enceladus-O Overview



- Enceladus Orbiter
  - 2.4-year mapping mission (45° inclined orbit, 200 km altitude), ~2% instrument data duty cycle
  - Two 24-hr polar campaigns at 100 km altitude
- Option for Hard Landers
  - Considered only as additional mass
- 2-Stage Spacecraft with Chemical Propulsion
  - Venus-Venus-Earth-Earth-Saturn Trajectory
    - $C3 = 19.05 \text{ km}^2/\text{s}^2$
  - Rhea flybys to reduce  $\Delta V$  needed to achieve orbit
  - Staging used to reduce mass needed in final orbit
  - Delta IV Heavy launch vehicle



# Enceladus Orbiter Instrument Science Value



Instrument	Mission Element	Included in Strawman Payload?	Biological Potential (Priority 1)	Tidal Heating and Interior Structure (Priority 2)	Composition (Priority 2)	Cryovolcanism (Priority 2)	Tectonics (Priority 2)	Surface Processes (Priority 3)	Saturn System Interaction (Priority 3)
Thermal Mapper	Enc. Orbiter	Y	8	9	2	8	5	2	0
Visible Mapper	Enc. Orbiter	Y	6	7	4	8	8	8	6
NIR Mapper	Enc. Orbiter	Y	7	3	8	5	3	5	5
Laser Altimeter	Enc. Orbiter	Y	8	9	2	5	7	4	0
USO	Enc. Orbiter	Y	8	9	2	4	6	1	0
Mag	Enc. Orbiter	Y	7	8	2	3	2	1	6
LC/GC-MS	Enc. Orbiter	Y	8	3	8	7	2	5	8
MEMSA	Enc. Orbiter	Y	8	3	8	8	1	4	6
Radar Sounder	Enc. Orbiter	Y/N*	6	8	4	7	6	5	0
Dust Analyzer	Enc. Orbiter	N	7	3	8	7	2	5	8
UV Spectrometer	Enc. Orbiter	N	3	2	5	6	0	3	7
Low Energy Plasma Analyzer	Enc. Orbiter	N	2	0	6	5	0	4	9
Energetic Particle Spectrometer	Enc. Orbiter	N	2	0	6	5	0	6	9
Penetrator Camera	Hard Lander	N	4	4	5	5	4	6	1
Transponder	Hard Lander	N	5	5	2	4	5	1	0
Seismometer	Hard Lander	N	5	9	3	6	8	4	0

\*Included on Enceladus Orbiter mission, not on Orbiter+Lander mission



# Enceladus Orbiter +/- Lander: Other Science Considerations



- Long pump-down period (using Rhea +/- Dione) provides many opportunities for second-level science (especially Saturn system interaction)
  - Large number of passes through the E-ring and neutral torus
  - Rhea provides a valuable “control” for understanding processes (e.g. impact cratering, differentiation) that are also important on Enceladus.
  - Dione’s resonance with Enceladus, extensive fracture system, and possible outgassing make it valuable both for the light it may cast on Enceladus, and as a target in its own right.
- 2.4-year Enceladus orbit lifetime is determined by downlink time
  - Driven mostly by requirement for 10-m/pixel global imaging in 4 colors
  - More aggressive data compression or subsampling would allow shorter orbital lifetime
- Orbital stability concerns limit number of polar passes for plume sampling and mapping of the active region
  - Still preferable to Saturn orbiter because of much lower speeds
  - High speed south polar passages during pumpdown phase might provide complementary coverage



# Saturn-O Science



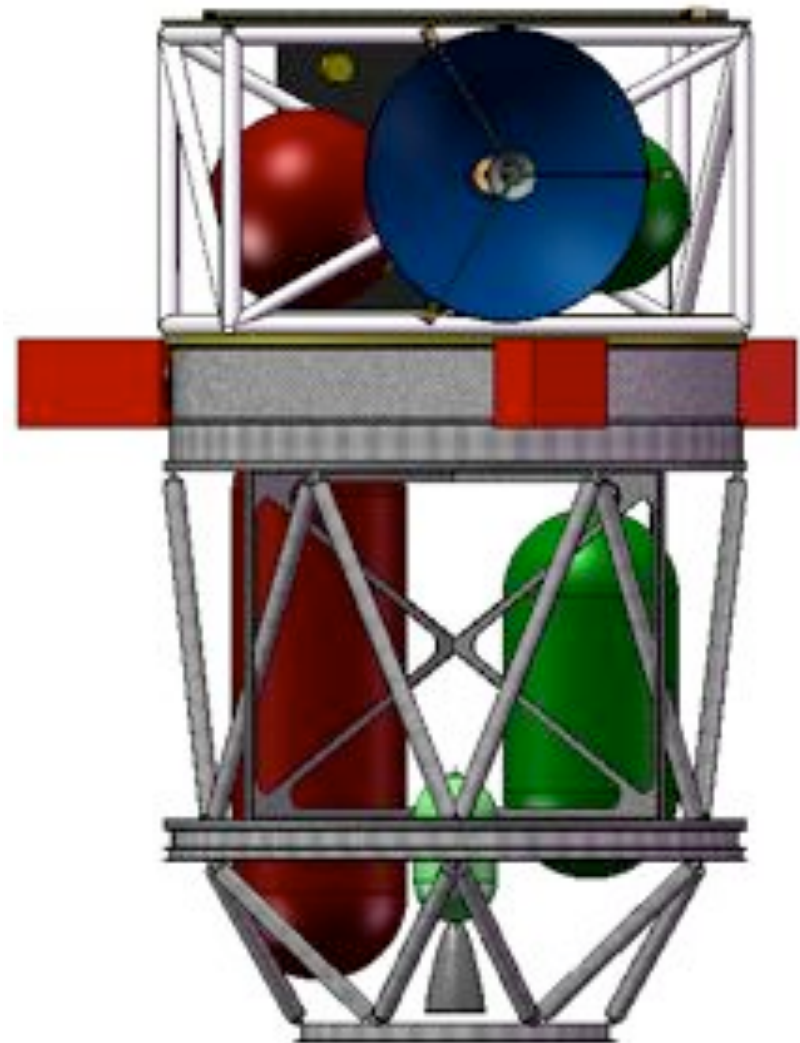
- Orbiter Science Drivers:
  - Same goals as for Saturn orbiter, except:
    - More precise measurements of gravity field and tidal deformation
    - Robust magnetic sounding for a subsurface ocean
    - Complete and consistent global morphological, compositional, and thermal mapping
    - Lower-speed plume sampling opportunities, for more detailed analysis of more pristine plume samples
    - Better communication relay for more detailed and robust surface observations
- Hard Lander Science Drivers:
  - High-frequency and low-frequency seismometry
    - Ice shell thickness, structure, cryovolcanism



# Saturn-O Results



- 6300 kg can be launched
- Total mission lifetime ~17.3 yr
  - 45° orbit achieved at ~L+15 yr
  - 11.75-yr trip time to SOI (worst case 12.25 yr)
  - ~ 9 months for Titan flybys
  - ~2.5 years and 30 Rhea flybys
- ~5870 kg gross mass (wet)
  - ~ 7 % launch margin
  - 85 kg science payload on orbiter
- Mission appears feasible
  - 30% reserve held on mass, power, data volume
    - Propellant determined based on mass including 30% reserve
    - 10%  $\Delta V$  reserve on maneuvers held in addition to 500 m/s overall  $\Delta V$  reserve
  - One fault tolerant design
    - Reliability for 17.3-year mission is still low
  - Trades can be made to: increase reliability, include hard landers, increase data duty cycle (decrease necessary mission life)

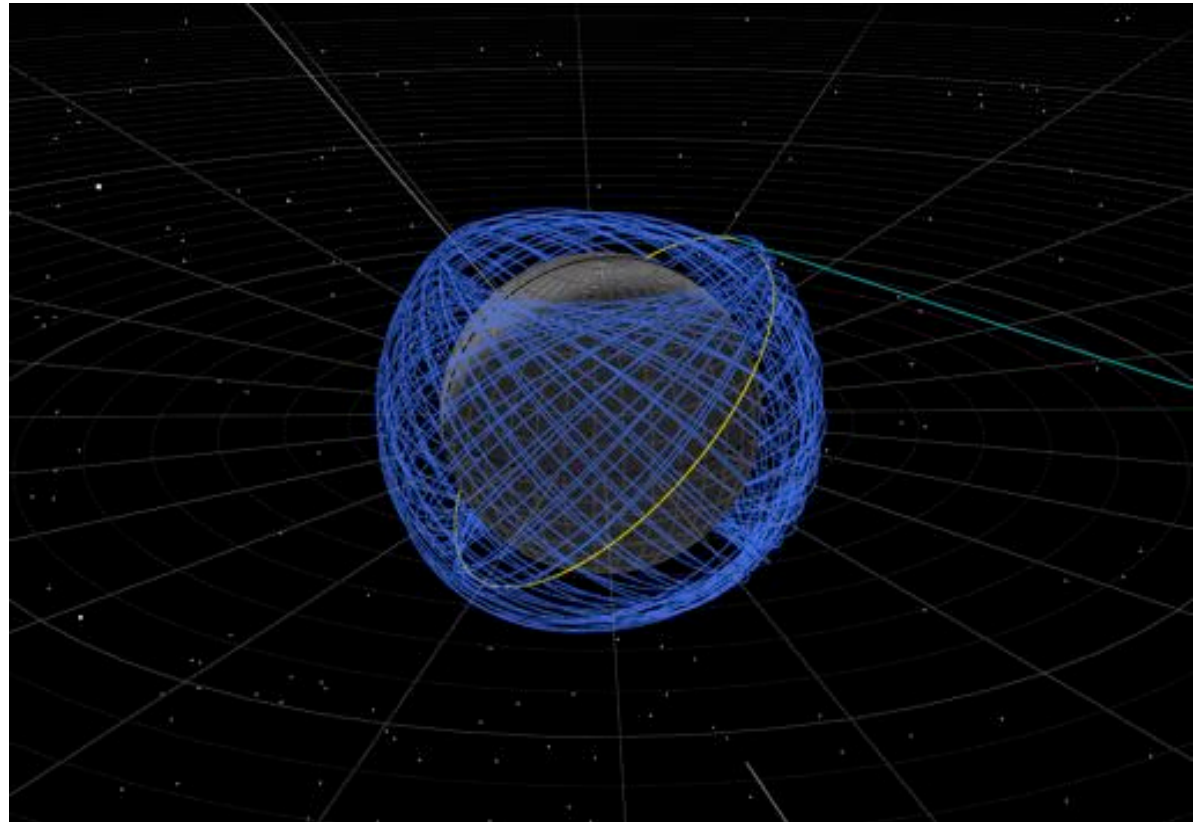




# Enceladus Mapping Orbit



- **Polar orbits not stable**
- **45 degree inclination is stable and provides acceptable remote sensing to ~60 N, and very oblique polar viewing**
- **Brief, data-intensive excursions to polar orbit provide plume passages and polar remote sensing**





# Enceladus-OL: Overview



- Enceladus Orbiter
  - 2.4-year mapping mission (45° inclined orbit, 200 km altitude), ~2% instrument data duty cycle
  - Two 24-hr polar campaigns at 100 km altitude
- Soft Lander
  - Battery powered, ~8-day lifetime
- 3-Stage Spacecraft (including Lander)
  - Chemical propulsion used for all 3 stages
  - Venus-Venus-Earth-Earth-Saturn Trajectory
    - $C3 = 19.05 \text{ km}^2/\text{s}^2$
  - Rhea & Dione flybys to reduce  $\Delta V$  needed
  - Staging used to reduce mass needed in final orbit
  - Delta IV Heavy launch vehicle



# Enceladus Orbiter + Lander: Instrument Science Value



Instrument	Mission Element	Included in Strawman Payload?	Biological Potential (Priority 1)	Tidal Heating and Interior Structure (Priority 2)	Composition (Priority 2)	Cryovolcanism (Priority 2)	Tectonics (Priority 2)	Surface Processes (Priority 3)
Thermal Mapper	Enc. Orbiter	Y	8	9	2	8	5	2
Visible Mapper	Enc. Orbiter	Y	6	7	4	8	8	8
NIR Mapper	Enc. Orbiter	Y	7	3	8	5	3	5
Laser Altimeter	Enc. Orbiter	Y	8	9	2	5	7	4
USO	Enc. Orbiter	Y	8	9	2	4	6	1
Mag	Enc. Orbiter	Y	7	8	2	3	2	1
LC/GC-MS	Enc. Orbiter	Y	8	3	8	7	2	5
MEMSA	Enc. Orbiter	Y	8	3	8	8	1	4
Dust Analyzer	Enc. Orbiter	N	7	3	8	7	2	5
UV Spectrometer	Enc. Orbiter	N	3	2	5	6	0	3
Low Energy Plasma Analyzer	Enc. Orbiter	N	2	0	6	5	0	4
Energetic Particle Spectrometer	Enc. Orbiter	N	2	0	6	5	0	6
Lander Camera (two)	Soft Lander	Y	4	4	5	5	4	8
Transponder	Soft Lander	Y	5	5	2	4	5	1
Seismometer	Soft Lander	Y	5	9	3	6	8	4
Surface Chemistry Package	Soft Lander	Y	9	2	9	6	2	7
LDMS	Soft Lander	Y	9	0	8	5	0	7
Surface Ice Oxidant Detector	Soft Lander	Y	8	0	7	5	0	7
Lander Magnetometer	Soft Lander	N	6	7	3	3	4	0
Lander NIR spectrometer	Soft Lander	N	6	0	6	3	0	7
Tunable Laser Spectrometer	Soft Lander	N	7	0	6	4	0	6



# Enceladus-OL Science



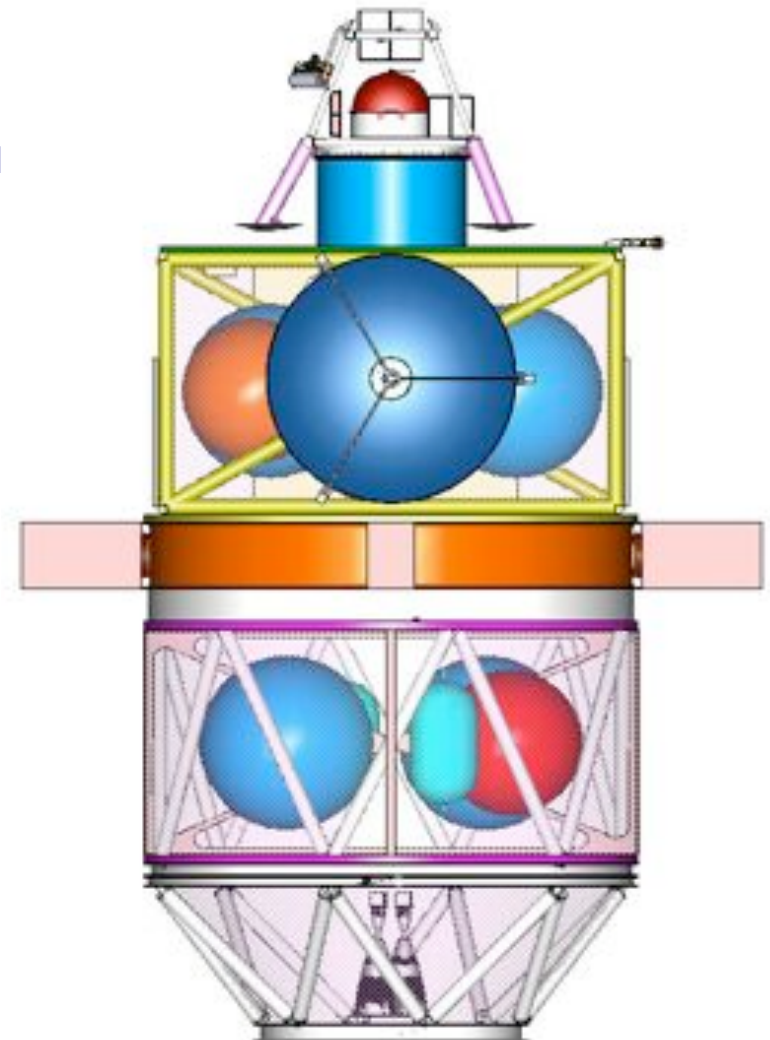
- Same as for Saturn-OL Lander and Enceladus-O Orbiter
- Best of both worlds
  - Excellent geophysics and mapping
  - Excellent chemistry



# Enceladus-OL Results



- 6300 kg can be launched
- Total mission lifetime ~18.3 yr
  - 45° orbit achieved at L+16 yr
  - 11.75-yr trip time (worst case 12.25 yr), Post SO Titan flybys
  - + 3.5 years and 43 Rhea & Dione flybys
- ~ 6300 kg gross mass (wet)
  - ~ 0 % launch margin
  - 73 kg science payload on orbiter
  - ~ 230 kg lander (wet mass)
    - ~20 kg payload
- Mission appears feasible, but zero launch margin
- 30% reserve held on mass, power, data volume
  - Propellant based on mass including 30% reserve
  - 10%  $\Delta V$  reserve on maneuvers held in addition to 500 m/s overall  $\Delta V$  reserve
  - One fault tolerant design
    - Reliability for 18.3-year mission is still low
  - Trades can be made to increase reliability, increase data duty cycle (decrease necessary mission life)

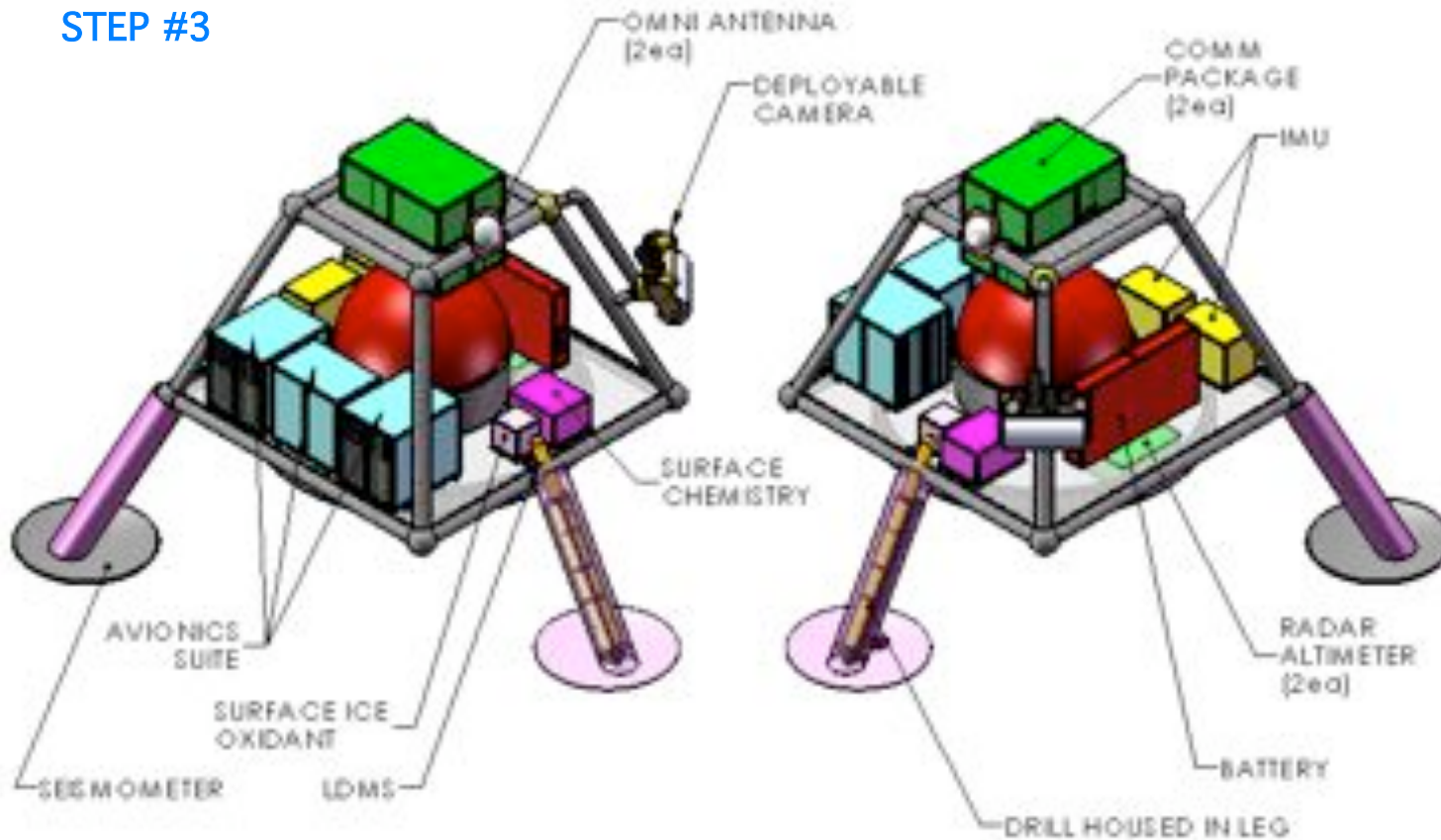




# Enceladus-OL Lander



STAGE #3  
STEP #3





# SDT Summary: Science Value of Mission Options Compared to Cassini



Science Value of Various Enceladus Mission Options				
Science Objectives	Enceladus Orbiter + Lander (Enceladus-OL)	Enceladus Orbiter (Enceladus-O)	Saturn Orbiter with Soft Lander (Saturn-OL)	Cassini Extended Mission
Level 1: Biological Potential	10: Excellent probing of interior and plume source region: excellent bulk analysis of surface materials	7: Excellent probing of interior and plume source region, plume characterization	8: Adequate probing of interior and plume, excellent bulk analysis of surface materials	3: Improved plume analysis, and understanding of the plume source region from remote sensing
Level 2: Composition	9: good plume chemistry, excellent surface chemistry of bulk samples	6: good plume chemistry, lack of bulk samples limits quality of analysis	8: Excellent surface chemistry of bulk samples	4 Improved plume sampling , limited by instrumentation
Level 2: Cryovolcanism	9 Low-speed plume sampling, extensive surface mapping and radar sounding (though limited in polar regions)	9 Low-speed plume sampling, extensive surface mapping and radar sounding (though limited in polar regions)	6: High-speed plume sampling and polar surface mapping	4: Improved remote sensing and in situ sampling, limited by instrumentation and small number of flybys
Level 2: Tectonics	9: global mapping, tidal flexing, altimetry, surface seismometry	8: global mapping, tidal flexing, altimetry, radar sounding	7: Orbital mapping with some limitations, surface seismometry	3: limited hi-res coverage, little geophysics
Level 2: Tidal Heating and Interior Structure	10: Excellent on tidal deformation, gravity, topography, magnetic sounding, excellent seismic sounding	8: Excellent on tidal deformation, gravity, topography, magnetic sounding	7: Adequate on tidal deformation, gravity, topography, poor on magnetic sounding, excellent seismic sounding	2: Some improved knowledge of the gravity field and heat flow
Level 3: Saturn system interaction	5: Good plume characterization, but no plasma instruments carried	5: Good plume characterization, but no plasma instruments carried	4: Good plume characterization (limited by high speed), but no plasma instruments carried	4: Multiple passes with good plasma instrumentation
Level 3: Surface Processes	9: Close-up imaging and direct surface sampling	7: Global hi-res mapping and composition	9: Close-up imaging and direct surface sampling	2: Very limited hi-res remote sensing, improved knowledge of plume resurfacing
<b>Relative Science Value (subjective rating based on the above matrix)</b>	<b>10</b>	<b>8</b>	<b>7</b>	<b>3</b>



# Some Other Promising Options



- Saturn Orbiter + Lander using small moon flybys to reduce delta-V
  - More mass for science instruments
  - Better science due to slower flybys
  - 2-4 year longer mission
- Enceladus orbiter with SEP
  - Need small moon flybys (including Tethys) to get payload mass in orbit comparable to chemical propulsion
  - Still, 3.5 year reduction in mission duration
- Enceladus sample return from Saturn orbit
  - Multiple sampling opportunities
  - Lower sample collection speeds
  - Still a very long mission



# Conclusions

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- Enceladus is a compelling science target
- Getting there is difficult and time-consuming, but doable
  - Use of small inner satellites to reduce delta-V requirements is key, but takes time
- Studies are still immature
  - Other mission architectures may be more promising than the ones studied in detail here
  - Subsequent trajectory work has identified improved trajectories (2-3 years shorter flight times, higher delivered mass)



# Back-up Material



# Lesser Moons $\Delta V$ Savings



	$\Delta V$ (m/s)	Savings (m/s)	Targeting (m/s)	Total- $\Delta V$ Savings (m/s)	Total- $\Delta V$ Cost (m/s)	Time (years)	Fly-bys
Titan	3780						
w/ Rhea	1830	1950	300	1650	2130	2.5	30
w/ Rhea & Dione	1220	2560	430	2130	1650	3.5	43
w/ Rhea, Dione & Tethys	700	3080	570	2510	1270	5.0	57

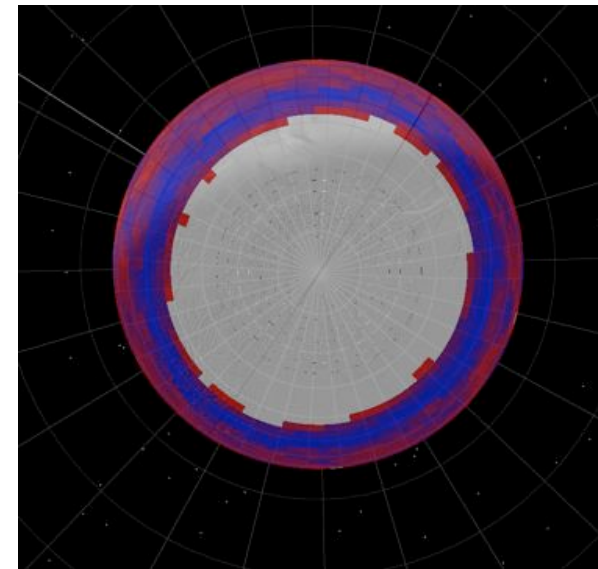
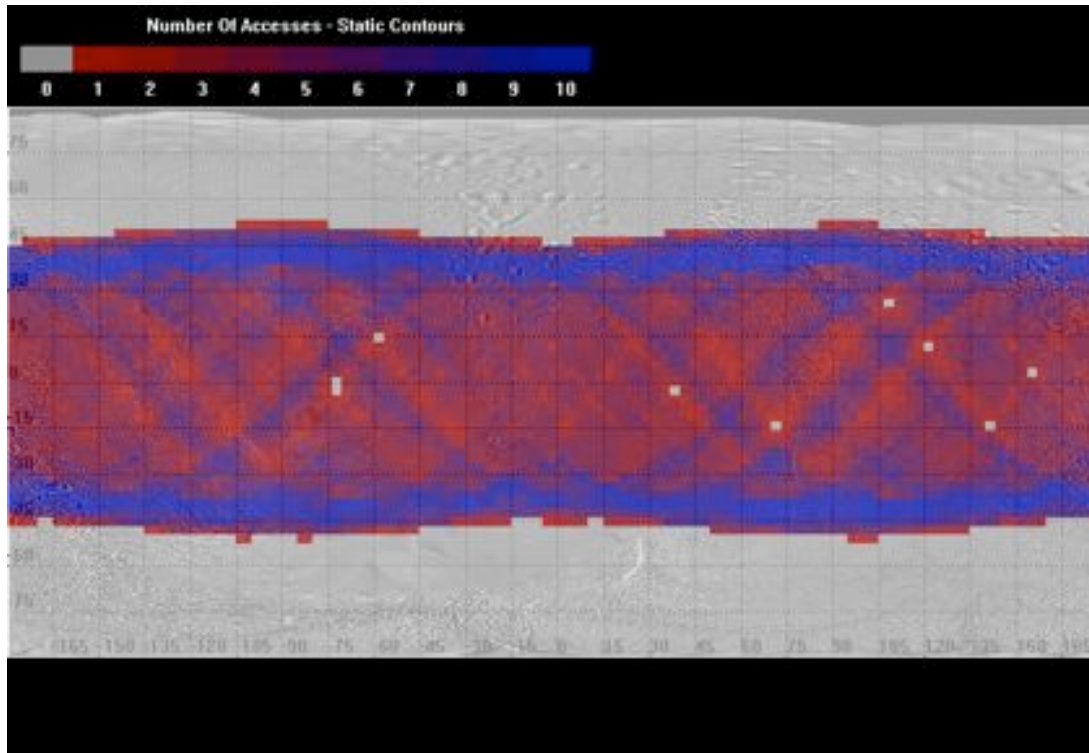


# Enceladus Mapping Orbit



12 days,  $i = 45^\circ$ , alt = 200km, Nadir Pointing

alt = 200km ==> TP = 6hr:20mn,  $V \sim 125$  m/s



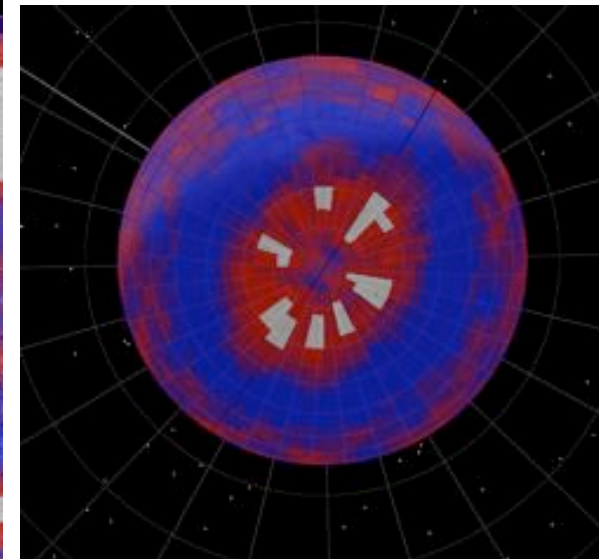
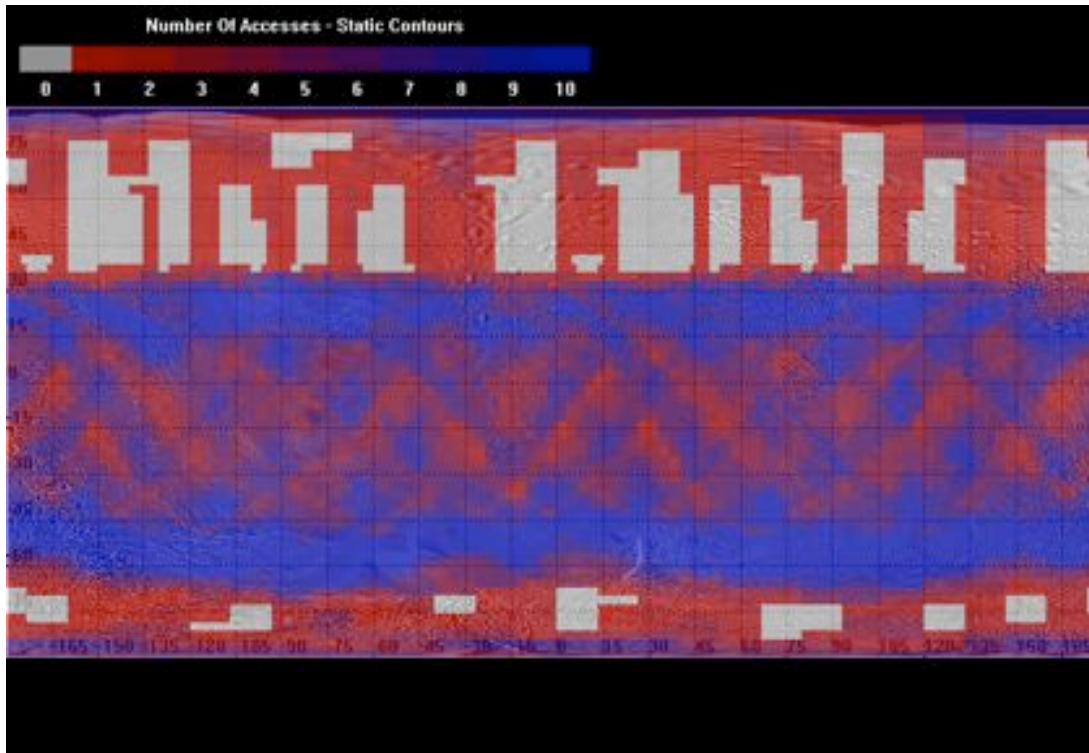
South Pole



# Enceladus Mapping Coverage



- 12 days,  $i = 45^\circ$ , alt = 200km,  $-18.35^\circ$  Offset Pointing
  - + 1 day,  $i = 90^\circ$ , alt = 100km, Nadir Pointing RA =  $0^\circ$
  - + 1 day,  $i = 90^\circ$ , alt = 100km, Nadir Pointing RA =  $180^\circ$
- alt = 200km ==> TP = 6hr:20mn,  $V \sim 125$  m/s  
alt = 100km ==> TP = 4hr:22mn,  $V \sim 142$  m/s



South Pole