Titan and Enceladus $1B Mission Feasibility Study

Exploring Mysterious Worlds

Study Lead:	K. Reh, Jet Propulsion Laboratory
Titan Principal Investigator:	R. Lorenz, Applied Physics Laboratory
Enceladus Principal Investigator:	J. Spencer, Southwest Research Institute
Mission Architect:	T. Spilker, Jet Propulsion Laboratory
Flight System Engineer:	J. Elliott, Jet Propulsion Laboratory
Cost Engineer:	E. Jorgensen, Jet Propulsion Laboratory

Executive Summary

Washington SAIC ARC GSFC KSC APL

Study Final Report

JPL D-37401 A
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Titan and Enceladus $1B Mission Feasibility Study Report

Prepared for NASA's Planetary Science Division

Prepared By:
Kim Reh

Contributing Authors:
John Elliott
Tom Spilker
Ed Jorgensen
John Spencer (Southwest Research Institute)
Ralph Lorenz (The Johns Hopkins University, Applied Physics Laboratory)

Washington SAIC KSC GSFC ARC APL

Approved By:

Kim Reh
Jet Propulsion Laboratory
Study Manager

Dr. Ralph Lorenz
The Johns Hopkins University, Applied Physics Laboratory
Titan Science Lead

Dr. John Spencer
Southwest Research Institute
Enceladus Science Lead

Pre-decisional — For Planning and Discussion Purposes Only

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JPL D-37401

The following members of an Expert Advisory and Review Board contributed to ensuring the consistency and quality of the study results through a comprehensive review and advisory process and concur with the results herein.

Name	Title/Organization	Concurrence
Gentry Lee	Chief Engineer/JPL Planetary Flight Projects Office	[signature]
Duncan MacPherson	JPL Review Fellow	[signature]
Glen Fountain	NH Project Manager/JHU-APL	[signature]
John Niehoff	Sr. Research Engineer/SAIC	[signature]
Bob Pappalardo	Planetary Scientist/JPL	[signature]
Torrence Johnson	Chief Scientist/JPL	[signature]

Agenda

- Study Objectives
- Study Approach & Findings

Context of Study

- Meant to address commitment by NASA to complete concept studies of Titan and Enceladus missions in 2006
- Quick turn-around: October -December
  - Mission elements are conceptual in nature
  - Total mission cost is parametric
- Draws from previous study results as well as Cassini-Huygens, NH and Juno experience

Study Objectives

- Determine feasibility of conducting missions to Titan and Enceladus within a $1B FY06 cost cap
- Characterize the science return achievable within a $1B FY06 cost cap
- Identify technologies required by the missions

Relationship to other outer planet missions

- Cassini-Huygens
  - A series of remarkable discoveries made by this NASA-ESA mission have stimulated interest in follow-up missions to Titan & Enceladus
    - Flagship mission >$3B total mission cost
    - Sets a high bar for missions in the sub $1B category
  - Any new mission must represent a sufficient advance in science
    - Make measurements not previously feasible
    - Extend coverage in space or time to unexplored areas
    - Make measurements of previously unknown phenomena
  - While Huygens is complete, Cassini is only 2 years into its prime mission
    - Four years of additional Titan and Enceladus observations has the potential to significantly impact science objectives and mission concepts
- New Horizons-Pluto (NH) and Jupiter Polar Orbiter (Juno)
  - The only two outer planet missions being implemented in the sub $1B cost range (NH~$800M; Juno ~$1B; FY06)
    - Insight into approaches for implementing cost capped outer planet missions
    - Benchmark for cost realism.

Ongoing experience used to inform and cross check study results

Study Guidelines

- Cost cap of $1B FY06
  - Includes spacecraft, launch vehicle, science instruments, radiosotope power system, mission operations, other mission elements and reserve
  - Does not include technology development
- Achieve sufficient increase in science understanding beyond Cassini-Huygens
  - As judged by SDT
- Use existing technology where possible
- Do not consider potential foreign contributions that could potentially defray costs
- Launch no earlier than 2015

Study Team

- *Titan Science
  - Ralph Lorenz (lead), APL
  - Elizabeth Turtle, APL
  - Frank Crary, SwRI
  - Hunter Waite, SwRI
  - Eric Wilson, JPL
  - Rosaly Lopes, JPL
- *Enceladus Science
  - John Spencer (lead), SwRI
  - Andy Ingersoll, Caltech
  - Amy Simon-Miller, GSFC
  - Bill McKinnon, WUStL
  - Chris McKay, ARC
  - Rich Terrile, JPL

*Members drawn from the outer planet community by NASA HQ

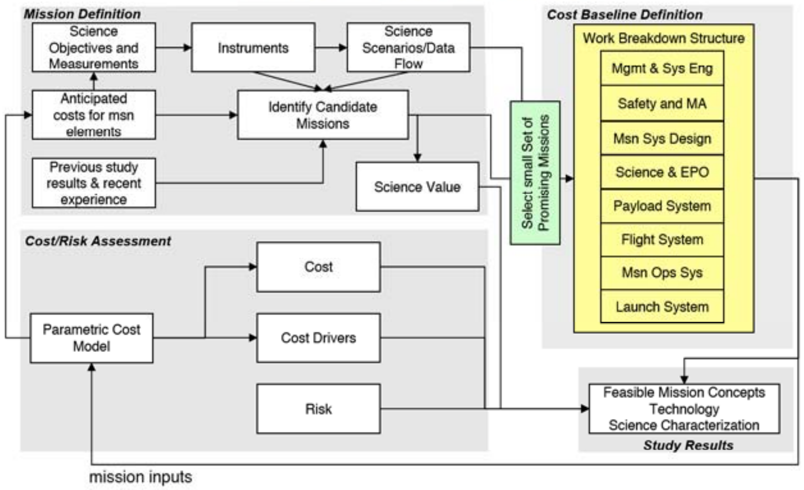
- Mission Architecture, System Engineering, Costing
  - Kim Reh, Ed Jorgensen, Tom Spilker, John Elliott, Greg Welz, Theresa Kowalkowski, JPL
  - Andrew Dantzler, APL
  - Norm Beck – KSC

- Expert Review & Advisory Group
  - Gentry Lee, JPL
  - Duncan MacPherson, JPL
  - Glen Fountain, APL
  - John Niehoff, SAIC
  - Bob Pappalardo, Torrence Johnson, JPL

KSC GSFC ARC

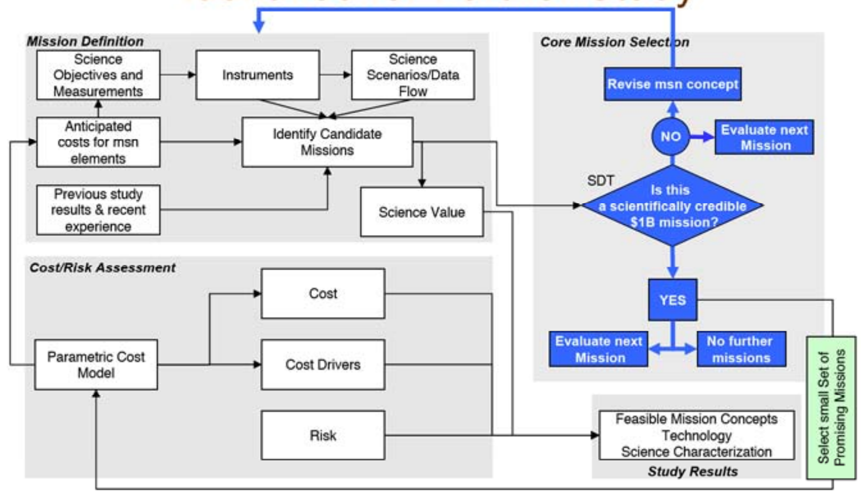
Tight integration of science & engineering personnel with extensive experience

Systematic Approach to Assess Alternatives



Structured to identify and assess feasibility of a broad set of missions

Smaller Set of Promising Missions Identified for Further Study



Narrowed a broad set of missions to a smaller set for cost modeling

24 Missions Identified

Titan and Enceladus Missions

ARCHITECTURAL ELEMENTS	#		MISSION SELECTION RATIONALE
Moon Orbiters with or without In Situ element	1	TITAN Orbiter+Lander	*multiple complex architectural elements – high cost*
	2	ENC Orbiter + Lander	*multiple complex architectural elements; large propulsion delta-V – high cost*
	3	Titan Orbiter+Aerobot	*multiple complex architectural elements – high cost*
	4	**TITAN Orbiter**	***Long dwell at Titan with new instrumentation enables complete and improved mapping of surface and upper atmosphere***
	5	ENCELADUS Orbiter	*delta-v too costly even with Titan aerocapture into Saturn orbit – high cost*
Saturn Orbiter with or without In Situ or Sample Return element	6	Sat Orbiter + TITAN Lander	*multiple complex architectural elements – high cost*
	7	Sat Orbiter+TITAN Aerobot	*multiple complex architectural elements – high cost*
	8	Sat Orbiter + TITAN Atm SR	*Sample integrity not assured (loss of volatiles, polymerization during sampling process); does not sample diverse locations, multiple complex architectural elements – high cost*
	9	Sat Orbiter + ENC Plume SR	*multiple complex architectural elements – high cost*
	10	Saturn Orbiter;TITAN & ENC Cycler	*Fewer FBs at ENC than at Titan. Insufficient increase in understanding beyond Cassini even with improved instrumentation – low science return*
	11	Sat Orbiter Multiple TITAN Fly-bys	*More FBs at Titan than at ENC. Insufficient increase in understanding beyond Cassini even with improved instrumentation – low science return*
	12	**Sat Orbiter Multiple ENC Fly-bys**	***new instrumentation could provide moderate science return beyond Cassini***
Single Fly-By with or without In Situ or Sample Return element	13	FB S/C + Titan Lander	*multiple complex architectural elements – high cost*
	14	FB S/C + ENC Inst Impactor	*only a few seconds of unique science prior to impact, not compelling – low science return*
	15	FB S/C + ENC Hard Lander	*multiple complex architectural elements – high cost*
	16	**FB S/C + TITAN Atm Probe**	***insufficient science increment beyond Huygens, low science return***
	17	FB S/C + TITAN Aerobot	*multiple complex architectural elements – high cost*
	18	TITAN Atm SR	*Limited atmospheric sample and return to earth - low science return*
	19	**ENCELADUS Plume SR**	***Potential value of science return is very high, mission is high risk: >10 km/s sample capture speeds and long duration >18 years***
	20	Single TITAN fly-by	*Provides no advance over Cassini - low science return*
	21	**Single ENCELADUS fly-by**	***science return not compelling even with new instruments compared to Cassini - low science return***
In Situ only	22	**TITAN Lander**	***new instrumentation enables surface chemistry; RPS enables long term MET and Seismic monitoring (new science) –*** *multiple battery landers not considered due to probable high cost. Single battery lander provides insufficient science.*
	23	ENCELADUS Lander	*Potentially valuable science, large propulsion delta-V to reach surface - high cost*
	24	**TITAN Aerobot**	***new instrumentation for chemistry, structure and long term meteorological & seismological monitoring (new science) – no surface sampling***

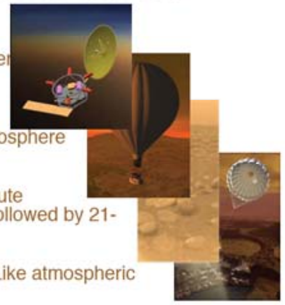
Core Titan Missions · Core Enceladus Missions

Initial Feasibility Assessment Results

- Broad set of 24 candidates assessed
  - 17 were ruled out for not meeting cost or science criteria by a substantial margin
- 7 cases warranted further study
  - Conceptual design and costing

Overview of 7 Promising Missions

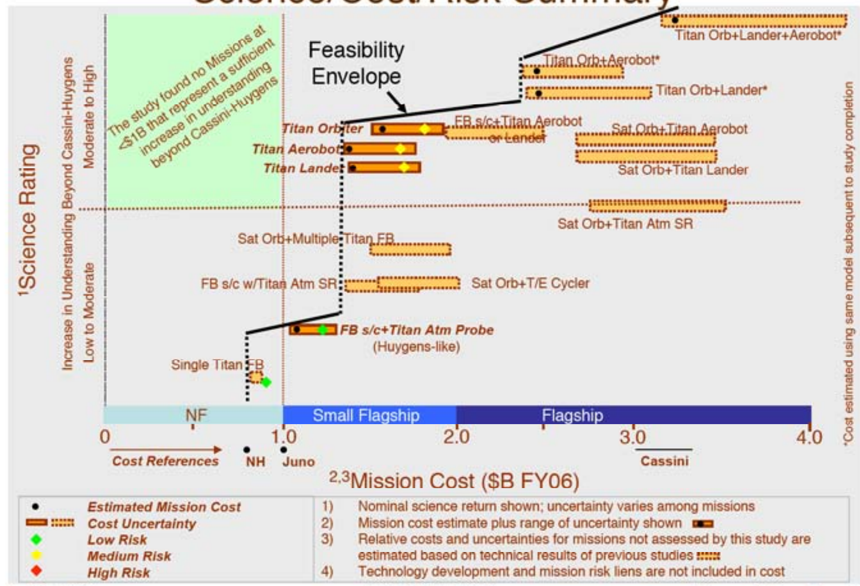
- **Titan**
  - **Titan Orbiter (4)** –aerocapture and braking into Titan's atmosphere 1500 km orbit; 2-year global mapping and atm. measurements.
  - **Titan Aerobot (24)** – direct entry into Titan; Montgolfiere hot air balloon at 10 km altitude; 1-year in situ science survey of atmosphere and surface
  - **Titan Lander (22)** - direct entry into Titan; Huygens style parachute soft landing; 3-month Viking-like surface sampling and imaging followed by 21-month seismic and meteorological monitoring
  - **Titan Atmospheric Probe (16) –** simple fly-by s/c for Huygens-Like atmospheric probe delivery and com relay; 4-8 hr encounter.



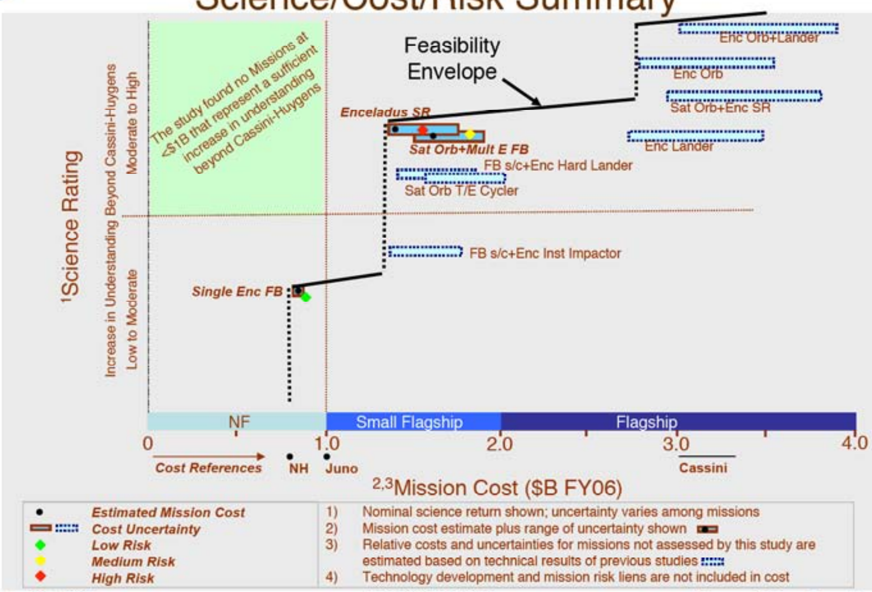
- **Enceladus**
  - **Saturn Orbiter with multiple Enceladus flybys (12)** - aerocapture into Saturn's orbit using Titan's atmosphere; targeted plume and global science via >30 Fly-Bys of Enceladus over 2-year period
  - **Enceladus Sample Return (19)** - sample capture >10 km/s; remote and in situ measurements; Earth free-return trajectory;18 year mission
  - **Enceladus Single Fly-By (21)** – NH-like mission using NH spacecraft with new but similar payload, single fly-by science return

These missions were subjected to a detailed feasibility analysis

Titan Results Science/Cost/Risk Summary



Enceladus Results Science/Cost/Risk Summary



Assessment of Science Value

- The SDT defined science objectives for Titan and Enceladus
- For each mission, the SDTs assigned a relative measure of how well each science objective would be met (scale 0-3).
- These relative measures were then used to synthesize an overall science value rating for each mission to represent how well that mission would advance the knowledge of Titan or Enceladus (scale 1-10).
- SDT determined that a science value in excess of 5 represented a "sufficient" advance in understanding beyond Cassini-Huygens to warrant investment in a $1B class mission.
- These ratings were influenced not only by past results of Cassini-Huygens but also by projected future results.
- The approach was straightforward but it did have limitations
  - Enables comparison of missions to same destination
  - Does not enable comparison of Titan missions with Enceladus missions

Cost Estimating Methodology

- Conceptual design developed for costing baseline
  - Flt/Gnd Systems based on information from previous studies and missions
  - Instruments, Mission architecture, operational scenario unique for each mission
  - Assumed 5 year (A-D) development schedule, 2018 launch date and 7 yr cruise
- Mission Cost estimates
  - WBS based to ensure that total life cycle costs are captured
  - Hybrid Outer Planet Cost Model
    - Historic factors for management, science, system engineering, mission assurance, etc.
    - PMCM for Spacecraft Parametric model e.g. mass, power, data rates, etc.)
    - NASA instrument cost model (NICM)
    - Ground Segment Cost Model for Msn Ops, GDS and DSN
    - DOE quotes for RPS costs
    - LV costs from KSC
  - Reserves added to account for implementation risk and design maturity
- Cost uncertainty ranges establish uncertainty in current level of technical implementation and fidelity of cost model
- Cost model checked against NH to test reasonableness of results
  - Reviewed by expert advisory board and independent experts
- Technology development costs not included (per study guidelines)

Assessment of Risk

- Implementation risks
  - Basis: top level risk sub-factor analysis
  - Costs included in TMC reserves
- Mission risks
  - Basis: most significant risks to mission completion
  - Mitigation costs carried as uncosted liens
- Technology risks
  - Basis: Technology for mission implementation
  - Mitigation not costed but recorded as uncosted liens

Study Conclusions

Science Value, Cost and Risk assessments were synthesized to form the basis for conclusions regarding feasibility:

- No missions to Titan or Enceladus, that achieve a sufficient increase in understanding beyond Cassini-Huygens, were found to fit within the cost cap of 1 billion dollars (FY'06)
- Three of the missions studied have the potential to meet the cost cap but fall below the science guideline established for this study
  - Single Fly-By of Enceladus
  - Single Fly-By of Titan
  - Single Fly-By of Titan with Atmospheric entry Probe (Huygens-like)
- Even the lowest cost mission option, **without the cost of science payload**, has a minimum expected cost of ~$800M making it highly unlikely that unexplored approaches exist that achieve sufficient science value for $1B
- All Titan and Enceladus missions that meet science guidelines require new technology development or flight validation

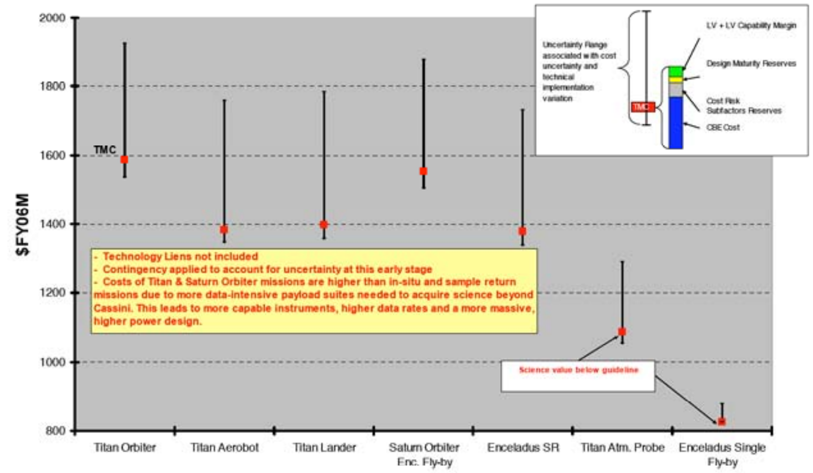
Recommendations

- Results of this study should be used as a stepping off point for follow-on NASA Flagship Studies
  - This has already occurred
- Development and Maturation of technologies necessary for Titan and Enceladus Flagship missions should be considered for programmatic funding, e.g.
  - Aerocapture (flight validation)
  - Aerial mobility (aerobots, onboard autonomy)
  - Low temperature materials and systems
  - Sample acquisition and organic analysis instrumentation
  - High speed sample capture (>10 km/s)
  - Returned sampling handling (biological potential)

SUPPLEMENTARY

K. Reh

Total Mission Cost Comparison



Cost Estimate Methodology

- The Total Mission Cost estimate uses a hybrid cost modeling approach including historic wrap factors and a mix of parametric cost models
  - PMCM (JPL Parametric model, performance driven: Mass, Power, Data Rate,...)
  - NICM (NASA model for instruments)
  - Ground Segment Team Cost Model used for MOS/GDS
- Reserves are calculated based upon Cost Risk Subfactors and design maturity
- Estimate ranges based upon cost model and technical implementation uncertainty
- Technology development costs are excluded from the estimate

WBS	Model Description
01 Project Management	Wrap factor based upon recent proposals and historic cost data analysis
02 Project System Engineering	Wrap factor based upon recent proposals and historic cost data analysis
03 Safety & Mission Assurance	Wrap factor based upon recent proposals and historic cost data analysis
04 Science Team	Scaled from historic cost data relationship between Science Team and instrument costs
05 Payload System	NASA Instrument Cost Model (NICM), analogy, Science Team evaluation
06 Spacecraft System	JPL Parametric Mission Cost Model (PMCM)
Radioisotope Power Source	RPS prices provided by DOE
07 Mission Operations System	JPL Ground Segment Team Cost Model
08 Launch System w/ Nuclear Support	KSC deflated to $FY06 using NASA inflation rates
09 Ground Data System	JPL Ground Segment Team Cost Model
DSN Aperture	JPL Ground Segment Team Cost Model
10 Project System Integration & Test	JPL Assembly, Test and Operations Cost Model (JACM)
11 Education and Public Outreach	Scaled at $10 FY06M
12 Mission Design	JPL Mission Design Cost Model
Reserves	JPL Cost Risk Subfactors and design maturity evaluation

Titan Orbiter

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	109	
01 Project Management	3	26	6	35
02 Project System Engineering	3	22	5	30
03 Safety & Mission Assurance	4	29	7	40
04 Science Team	6	16	60	83
05 Payload System	16	140	0	156
2 Micron Imager	3	28		31
Plasma package (orbiter only)	3	28		31
Imaging Radar / Altimeter	6	53		59
Chemical Analyzer	3	27		30
Radio Science	1	5		6
06 Spacecraft System	49	439	0	487
06.01 S/C Management	1	12		13
06.02 Spacecraft System Engineering	2	17		19
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	17	156		174
Power SS	1	9		10
Radioisotope Power Source	16	148		164
06.05 C&DH SS	1	13		15
06.06 Telecom SS	2	22		24
06.07 Mechanical SS	3	30		33
06.08 Thermal SS	4	40		45
06.09 Propulsion SS	1	11		12
06.10 GN&C SS	2	21		24
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	1	11		12
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	13		14
06.20 SEP	10	92		103
07 Mission Operations System	1	15	58	74
09 Ground Data System	2	13	9	25
DSN Aperture	0	2	24	26
10 Project System Integration & Test	0	23		23
11 Education and Public Outreach	1	3	6	10
12 Mission Design	4	6		9
CBE Cost (Reserves Base)	88	734	176	997
Reserves	40	338	35	413
08 Launch System w/ Nuclear Support	17	149		166
LV Reserve	1	9		10
Total Mission Cost ($FY06)	145	1,229	211	1,586

Assumptions

- Development schedule and cruise to Saturn similar for all concepts
  - 5 year Phase A-D development
  - 7 year Cruise to Saturn
    - assumes SEP thrusting operations for 3 years, requiring a standard crew followed by 4 years of quiet cruise permitting reduced staffing
    - 6 to 9 months prior to encounter, staffing is ramped up for checkout and preparation for encounter
- 2018 launch date baselined
- Planetary protection
  - Aerobot / Lander: Category 2
  - Sample Return: Category 2 (uncosted lien for Category 3 (outbound) / Category 5 (inbound))
  - Orbiters: Category 2
- Use existing expendable launch vehicle
  - Exclude Delta4H due to cost
  - LV cost reserves held for potential mass growth
- MMRTGs available for launch

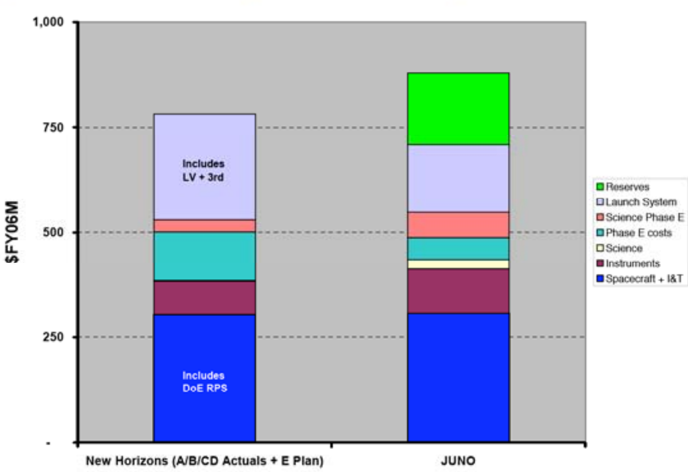
Uncosted Liens

high (C >$50M) medium ($10M< C <$50M) low (C<$10M)

Mission	Risk	Technology/Development Cost Lien
Titan Orbiter	-orbit insertion	-aerocapture demonstration (high)
Titan Aerobot	-first time in Titan cryogenic environment	-low temperature systems/materials (low)
Titan Lander	-sample acquisition handling, -operation in cryogenic environment	-in situ instruments (medium) -sample handling (medium) -low temperature systems/ materials (low)
Enceladus Sample Return	-plume longevity -uncertainty in plume particle impact hazard to s/c -very high speed particle capture - >18 year mission life -planetary protection-forward and back contamination	-additional plume analysis and modeling using Cassini data (low) -sample capture system >10 km/s, 1-3 micron particles (high) -increased reliability analysis, life testing and robust design (medium) -planetary Cat 2 (uncosted lien for Cat 3 (outbound) / Cat 5 restricted (inbound), (medium) -sample curation facility (high)
Saturn Orbiter Multiple Enceladus Fly-bys	-Titan Aerocapture into Saturn orbit	-aerocapture demonstration (high)

No additional risks beyond what is captured in TMC reserves were identified for Titan Atmospheric Probe and Enceladus or Titan Single Fly-by

Cost profile for existing outer solar system missions <$1B



NH and Juno are simple missions relative to what will be needed to build upon the discoveries of Cassini-Huygens at Titan & Enceladus

Instruments

	Instrument	$FY06M	Description
Titan Orbiter	2 Micron Imager	30.6	CRISM analogy
	Plasma package (orbiter only)	30.7	NICM
	Imaging Radar / Altimeter	58.6	NICM
	Chemical Analyzer	30.0	NICM evaluation + Science Team
	Radio Science	6.0	Cassini Radio Science analogy
	Total	**155.9**	
Titan Aerobot	Survey Camera Suite	4.5	NICM
	Met Package	5.0	Netlander analogy
	Profiling/Subsurface Radar	16.6	NICM
	Gas Chromatograph Mass Spectrometer	35.0	Science Team estimate
	TDL Spectrometer (ethane,methane, HCN)	4.0	NICM
	Total	**65.1**	
Titan Lander	Chemical Analyzer with Surface Sampling	73.0	Placeholder . To meet w/ MSL
	Lander Camera	5.0	MER PanCam analogy
	Seismometer	16.0	Netlander analogy + $6M for deployment arm
	Met Package	5.0	Netlander analogy
	Descent Camera	3.0	NICM evaluation + Science Team
	Total	**102.0**	
Enceladus Sample Return	Visible Imager	15.0	NICM evaluation + Science Team
	Thermal Mapper	15.0	NICM evaluation + Science Team
	High-Resolution INMS	30.0	NICM evaluation + Science Team
	Advanced Dust Analyzer	15.1	NICM
	Sample Collection System	16.9	Stardust analogy. SRC + Aerogel Dust Collector
	Total	**92.0**	
Saturn Orbiter - Enc Fly-by	Visible Imager	15.0	NICM evaluation + Science Team
	Thermal Mapper	15.0	NICM evaluation + Science Team
	Radar sounder	25.0	MARSIS analogy
	Magnetometer	3.4	NICM
	High-Resolution INMS	30.0	NICM evaluation + Science Team
	Advanced Dust Analyzer	15.1	NICM
	Radio Science	6.0	Cassini Radio Science analogy
	Total	**109.5**	
Titan Atmospheric Probe	Met Package	5.0	Netlander analogy
	Profiling/Subsurface Radar	16.6	NICM
	Gas Chromatograph Mass Spectrometer	35.0	Science Team estimate
	Descent Camera	3.0	NICM evaluation + Science Team
	Total	**59.6**	
Enceladus Single Fly-by			
	Visible Imager	15.0	NICM evaluation + Science Team
	Thermal Mapper	15.0	NICM evaluation + Science Team
	High-Resolution INMS	30.0	NICM evaluation + Science Team
	Advanced Dust Analyzer	15.1	NICM
	Total	**75.1**	

Feasibility Results

#	Target	In Space Flight System	In Situ Flight System	Sample Return System	Cost	Science
1	Titan	Moon Orbiter	Lander			
2	Enceladus		Lander			
3	Titan		Aerobot			
4	Titan					
5	Enceladus					
6	Titan	Saturn Orbiter (multiple moon fly-bys)	Lander			
7	Titan		Aerobot			
8	Titan		Atmospheric sampler	Earth entry capsule		
9	Enceladus		Plume sampler	Earth entry capsule		
10	Titan/Enc (cycler)					
11	Titan					
12	Enceladus					
13	Titan	Fly-By Spacecraft	Lander			
14	Enceladus		Impactor			
15	Enceladus		Hard Lander			
16	Titan		Atmospheric probe			
17	Titan		Aerobot			
18	Titan		Atmospheric sampler	Earth entry capsule		
19	Enceladus		Plume Sampler	Earth entry capsule		
20	Titan					
21	Enceladus					
22	Titan	Simple Cruise Stage	Lander			
23	Enceladus		Lander			
24	Titan		Aerobot			

Highest value

Bounding case for low cost

Missions Costed for Feasibility
Fails by wide margin
Fails by small margin
Succeeds by small margin
Succeeds by large margin
Optimal Solution

Titan Science Value

Relative Science Value of Titan Missions
Increase in Understanding Beyond Cassini-Huygens

Mission: Flagship Class, Total Mission Cost (TMC)>$2B; Small Flagship Class $2B>TMC>$1B; NF Class TMC<$1B

Science Objectives	Titan Orbiter + Lander + Aerobot	Titan Orbiter + Lander	Titan Orbiter + Aerobot	Saturn Orbiter + Titan Lander	Saturn Orbiter + Titan Balloon	Saturn Orbiter + Titan Sample Return	Saturn Orbiter; Titan/Enc Cycler	Fly-By S/C + Titan Lander	Fly-By S/C + Titan Aerobot	Titan Orbiter	Titan Lander	Titan Balloon	Saturn Orbiter w/Multiple Titan Fly-Bys	FlyBy S/C + Atm Sample Return	Single Titan Fly-By w/Atm Probe	Single Titan Fly-By w NH s/c
Sources of Methane																
Condensation and Cloud Formation																
Methane Conversion																
Aerosol Formation																
Surface Organic Inventory																
Geomorphology and Transport																
Surface Composition																
Overall Mission Rating	10.0	8.0	8.5	6.3	6.8	5.0	3.0	6.0	6.0	7.0	6.0	6.5	4.0	3.0	2.0	0.5

Code for rating of Science Objectives (relative to Cassini-Huygens): Very large increment beyond Cassini; Large increment beyond Cassini-H; Small increment beyond Cassini-H; Redundant with Cassini-H

Code for Overall Science Rating of Mission (1-10 relative to Cassini Huygens with 5 being sufficient): 1,2 fails by large margin; 3,4 fails by small margin; 5,6,7 succeeds by small margin; 8,9 succeeds by large margin; 10 optimal solution

Indicates missions chosen for costing

Enceladus Science Value

Relative Science Value of Enceladus Missions: Increase in Understanding Beyond Cassini/Huygens

Mission: Flagship Class TMC>$2B; Small Flagship Class $2B>TMC>$1B; NF Class TMC<$1 B

Science Objectives	Enceladus Orbiter + Lander	Enceladus Orbiter	Enceladus Lander	Saturn Orbiter + Enceladus SR	Saturn Orbiter; Titan/Enc Cycler	Fly-By S/C + Enc Inst Impactor	Fly-By S/C + Enc Hard Lander	Enceladus Sample Return	Saturn Orbiter w/Multiple Enc Fly-Bys	Single Enceladus Fly-By
Tidal Heating										
Interior Structure										
Bulk Composition										
Tectonics										
Cryovolcanism										
Surface Processes										
Biological Potential										
Relative Mission Science Value	10	9	7	8	6	4	6	7	7	3

Indicates missions chosen for costing

Code for rating of Science Objectives (relative to Cassini-Huygens): Very large increment beyond Cassin; Large increment beyond Cassini-H; Small increment beyond Cassini-H; Redundant with Cassini-H

Code for Overall Science Rating of Mission (1-10 relative to Cassini Huygens with 5 being sufficient): 1,2 fails by large margin; 3,4 fails by small margin; 5,6,7 succeeds by small marc; 8,9 succeeds by large marg; 10 optimal solution

Mission Risk

Significant Risks	Cost impact H:C>$50M M:$10M<C<$50M L:C<$10M	Titan Orbiter	Titan Aerobot	Titan Lander	Titan Atmospheric Probe	Enceladus Sample Return	Saturn Orbiter w Multiple Enc FBs	Single Enceladus FB
Entry, Descent and Landing								
Aerocapture								
Materials and systems for cryogenic environment								
Sample acquisition and handling								
Existance of Plume at time of arrival								
Plume particle impact hazard								
Hypervelocity particle capture								
>18 year mission life								
Curation facility for returned samples								
Overall Mission Risk Rating								

Enceladus Sample Return: **highest risk**
- Plume hazards
- Hypervelocity sample capture technology
- Long lifetime components and systems
- Curation facility

Titan Orbiter & Saturn Orbiter: **medium risk**
- Aerocapture technology
- Plume particle impact

Titan Lander and Aerobot: **medium risk**
- Uncertainty in EDL performance in a new environment
- Low temperature components and systems

Titan Atmospheric Probe and Enceladus Single Fly-By: **lowest risk**
- missions and systems have already been demonstrated in flight

Risk ratings based on Consequence and Likelihood
Mitigations are carried as Uncosted Liens

Risk Assessment

Significant Risks	Cost impact H:C>$50M M:$10M<C<$50M L:C<$10M	Titan Orbiter	Titan Aerobot	Titan Lander	Titan Atmospheric Probe	Enceladus Sample Return	Saturn Orbiter w Multiple Enc FBs	Single Enceladus FB
Entry, Descent and Landing	M							
Aerocapture	H							
Materials and systems for cryogenic environment	L							
Sample acquisition and handling	M							
Existance of Plume at time of arrival	L							
Plume particle impact hazard	L							
Hypervelocity particle capture	H							
>18 year mission life	M							
Curation facility for returned samples	H							
Overall Mission Risk Rating		med	med	med	low	high	med	low

Enceladus Sample Return: **highest risk**
- Plume hazards
- hypervelocity sample capture technology
- long lifetime components and systems
- Curation facility

Titan Orbiter and Saturn Orbiter: **medium risk**
- aerocapture technology
- Plume particle impact

Titan Lander and Aerobot: **medium risk**
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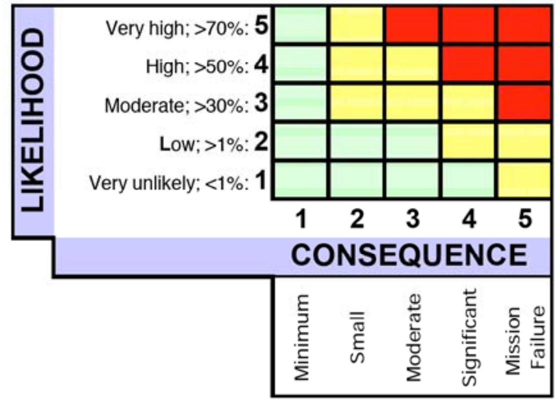
Risk Ratings



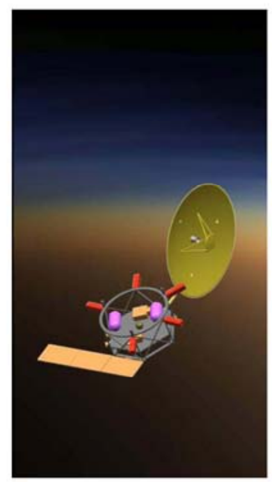
Feed Forward Approach

Previous Europa Activities	*$1B Dollar Titan and Enceladus Mission Feasibility Studies*	*Europa Flagship Study*
	Science valuation approach Quantification of science value for each concept (objective results validated by subjective assessment)	**Adopted, further refined to illustrate mission success and descope strategy**
	Structured approach to assess alternative concepts	**Partially adopted, candidate mission architecture directed by headquarters (Europa orbiter)**
Outer Planets Cost Model (Validated against Cassini)	**Outer Planets Cost Model** PMCM (JPL Parametric model, performance driven: mass, power, data rate,...) for Spacecraft; NICM (NASA model for instruments); JPL Ground Segment Team Cost Model for MOS/GDS **(Validated with New Horizons)**	**Adopted for Europa Study with modification to use grass roots for Spacecraft Costing**
	Reserve strategy based on JPL Cost Risk Sub-factor Analysis and Design Maturity	**Adopted**
Cost Driver Identification	**Adopted**	**Adopted**

Titan Orbiter

- Scientific Objectives:
  - Global IR and radar mapping from 1500 km (altitude) orbit; composition of complex organics and precursors in upper neutral atmosphere
- Exploration Metrics:
  - SEP stage used to shorten trip time, increase delivered mass
  - Aerocapture into Titan orbit, aerobrake to final orbit
  - 4 MMRTGs provide electrical power
  - Mapping phase to last two years
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

*Per NASA NPR: 7120



Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

- Science Payload:
  - Multi-channel 2-μ IR imager
  - Ku-band SAR/altimeter
  - Gas chromatograph/mass spec
  - Integrated plasma instrument suite
  - Radio science
- Technology & Heritage:
  - Heritage from previous orbiters
  - MMRTG to be flown on MSL
  - Aerocapture technology validation required
- Mission/Technology Studies:
  - Titan aerocapture study (2003)
  - TiPEx Study (2006)
  - Team X Titan Orbiter Study (2006)
  - Team X Enceladus Studies (2006)

Titan Aerobot

- Scientific Objectives:
  - Detailed remote sensing and *in situ* survey of atmosphere and surface features (no surface contact), riding Titan's winds at a few km altitude
- Exploration Metrics:
  - SEP stage used to shorten trip time, increase delivered mass
  - Direct entry into Titan atmosphere
  - 2 MMRTGs provide buoyancy and electrical power
  - Nominal 1-year mission
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

- Science Payload:
  - Down- & side-looking cameras
  - Meteorology instrument suite
  - Radar altimeter/subsurface sounder
  - Gas chromatograph/mass spec
  - Tunable diode laser spec
- Technology & Heritage:
  - Some Huygens heritage
  - Balloon technology in development at JPL
  - MMRTG to be flown on MSL
  - Low-temperature operations
- Mission/Technology Studies:
  - Titan Vision Mission Study (2005)
  - TiPEx Study (2006)
  - Technology studies in in-space propulsion, low-temperature materials, and autonomy

*Per NASA NPR: 7120

Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

Titan Lander

- Scientific Objectives:
  - Viking-like surface science, including sampling and imaging
  - Meteorological and seismic measurements continue in extended mission
- Exploration Metrics:
  - SEP stage used to shorten trip time, increase delivered mass
  - Direct Entry into Titan atmosphere, Huygens-style parachute landing
  - 2 MMRTGs provide electrical power
  - 90 day sampling mission followed by 21-month meteor-ological & seismic monitoring mission
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

- Science Payload:
  - Descent imager
  - PANCAM-like surface imaging
  - Meteorology instrument suite
  - Surface chemistry analysis
  - Seismometers
- Technology & Heritage:
  - Some Huygens, Mars lander heritage
  - MMRTG to be flown on MSL
  - Low-temperature operations
- Mission/Technology Studies:
  - Technology studies in in-space propulsion, low-temperature materials, and autonomy

*Per NASA NPR: 7120

Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

Titan Atmospheric Probe

- Scientific Objectives:
  - High resolution surface studies over limited region of interest.
  - Ground truth for different latitude/season than Huygens
- Exploration Metrics:
  - Larger parachute to permit longer descent and drift ground track than Huygens (but chute initially reefed to quickly descend to clear levels in lower atmosphere?)
  - Aim for known target of interest (volcano? Lake?)
  - Surface science opportunistic only (as Huygens)
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

- Science Payload:
  - Descent Imager
  - Gas chromatograph/mass spec with aerosol sampler
  - Atm. structure/MET package
  - Radar altimeter/sounder
  - Doppler Tracking/VLBI

Technology & Heritage:
- Heritage Huygens / DS2 / MER
- S-band uplink to relay s/c
- Lithium primary battery

Mission/Technology Studies:
- Titan aerocapture study (2003)
- TiPEx Study (2006)
- Team X Titan Orb Study (2006)
- Team X Enc Studies (2006)

Note that this mission concept's science return was considered insufficient even with improved instrumentation compared to Cassini

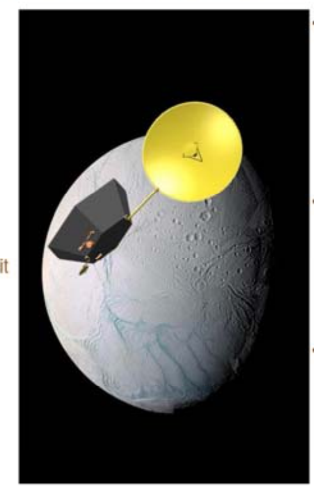
*Per NASA NPR: 7120

Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

Saturn Orbiter/Multiple Enceladus Flyby

- Scientific Objectives:
  - Remote sensing and *in situ* plume science, and global remote sensing observa-tions, during multiple close flybys of Enceladus
- Exploration Metrics:
  - SEP stage used to shorten trip time, increase delivered mass
  - Aerocapture into Saturn orbit using Titan's atmosphere
  - 4 MMRTGs provide electrical power
  - >30 flybys over a 2-year period
- Mission & LV Class:
  - Class A, Category 1*
  - EELV



- Science Payload:
  - Visible and thermal-IR mappers
  - Subsurface sounding radar
  - Dust/gas analyzers
  - Magnetometer
  - Radio science
- Technology & Heritage:
  - Heritage from previous orbiters
  - MMRTG to be flown on MSL
  - Aerocapture technology validation required
- Mission/Technology Studies:
  - Titan aerocapture study (2003)
  - Team X Enceladus Mission Studies (2006)

*Per NASA NPR: 7120

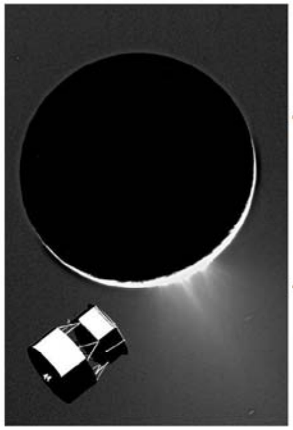
Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

Enceladus Plume Sample Return

- Scientific Objectives:
  - Return sample of plume material to Earth with intact organics
  - Remote sensing and *in situ* support science
- Exploration Metrics:
  - SEP stage used to shorten trip time, increase delivered mass
  - Free-return trajectory gives total mission time ~20 years
  - Simple flyby spacecraft design
  - 2 MMRTGs provide electrical power
  - Sample capture at >10 km/s
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

*Per NASA NPR: 7120



- Science Payload:
  - Visible and thermal-IR imagers
  - Dust/gas analyzers
  - Sample capture/return apparatus
- Technology & Heritage:
  - Heritage from Stardust, Genesis
  - MMRTG to be flown on MSL
  - Intact capture of organics at >10 km/s not yet demonstrated
- Mission/Technology Studies:
  - Team X Enceladus Mission Studies (2006)

Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

Enceladus Single Flyby

- Scientific Objectives:
  - Concentrated Enceladus observations during single flyby
- Exploration Metrics:
  - Mission concept based on New Horizons
  - Simple ballistic flyby trajectory
  - New Horizons spacecraft design
  - Single GPHS RTG provides electrical power
- Mission & LV Class:
  - Class A, Category 1*
  - EELV

*Per NASA NPR: 7120

- Science Payload:
  - Visible and thermal-IR imagers
  - Dust/gas analyzers
- Technology & Heritage:
  - Flight system assumes New Horizons design
- Mission/Technology Studies:

Note that this mission concept's science return was considered insufficient even with improved instrumentation compared to Cassini

Earliest Launch Opportunity: 2018**

** Programmatic, not technical, constraint

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