National Aeronautics and Space Administration

RADIOISOTOPE
POWER SYSTEMS

# Radioisotope Power System-based Enceladus SmallSat Mission Concept: *Enceladus Express*

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POWER TO EXPLORE


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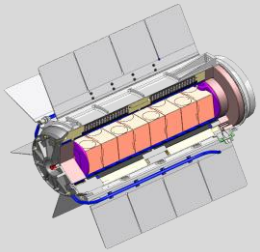
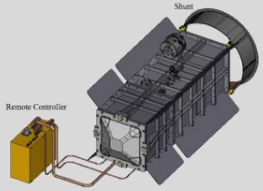
# Radioisotope Power Systems

- Radioisotope Power Systems (RPS) are enabling for many deep space mission concepts, particularly for outer planet destinations
- RPS use the decay of a radioisotope (Pu-238) as a heat source, and convert the heat to electrical power via various methods.
  - Radioisotope Thermoelectric Generators (RTGs) use Thermoelectrics (TE), which create a voltage via the Seebeck effect.
  - Stirling Radioisotope Generators (SRGs) would use Stirling engines, which use the heat to drive pistons and then convert the motion into electricity.
- Current RPS use general-purpose heat source (GPHS) modules as heat sources
  - For the purpose of this assessment, each GPHS module is assumed to produce 250 $W_{th}$ at beginning of life (BOL)

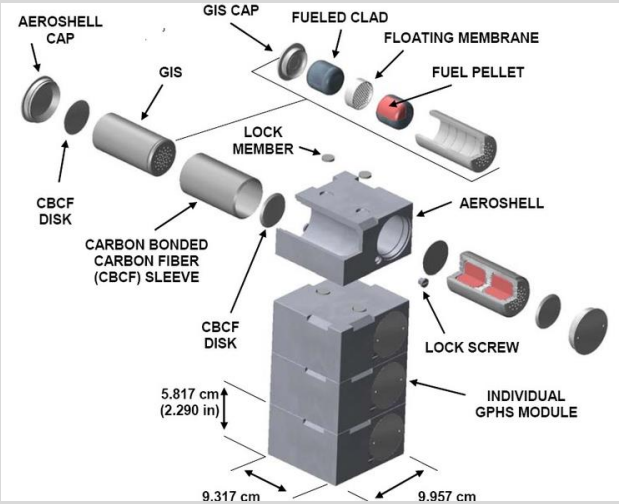


Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)




Advanced Stirling Radioisotope Generator (ASRG) Concept

GPHS Exploded View



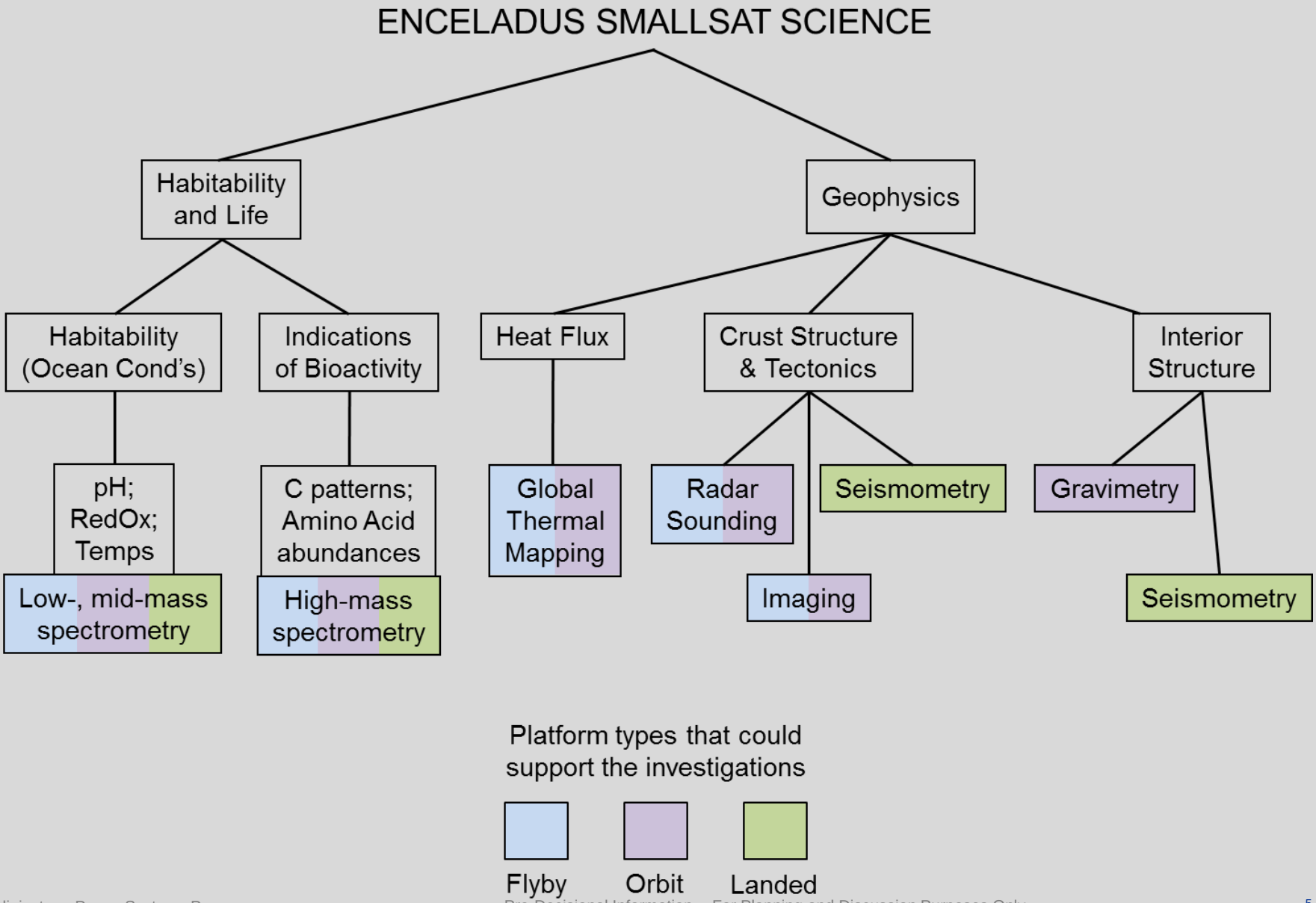
# Rationale for RPS SmallSats

- Need for affordable deep space missions
  - NASA and Mission Community strongly desire smaller missions to more destinations for lower cost
- Outer Planets SmallSats
  - Spacecraft in the 100-500 kg mass range could lower mission costs while still performing significant science
  - The challenges of exploration beyond Mars/Jupiter may not be feasible for SmallSats using solar arrays
    - Solar power in the outer solar system could require very large arrays, which in turn could require support from large spacecraft structures.
    - Thermal management in the outer solar system could be prohibitively power-expensive.
- RPS for SmallSats
  - RPS can provide power and heat at any distance from the sun
  - However, the mass and cost of currently available RPS present their own challenges

# Enceladus Express Concept - Executive Summary

- The study developed two concepts for Enceladus SmallSats in the 200-400 kg class
  - Enceladus was chosen due to its strong science draw and the applicability of RPS
  - Mission would include two nearly-identical (different only in the instrument payload) SmallSats launched together, each powered by a single MMRTG
  - Targeting NF cost category
- The study concluded that RPS Outer Planets SmallSats are feasible
  - Mission concepts closed mass and power budgets, and were relatively generic designs that could be adapted to other destinations
  - RPS lowers risk for Enceladus plume sampling mission
  - RPS enables aerocapture/gravity assist, which may be an enabling technology for exploring the gas giants with SmallSats

# Science Objectives and Investigations

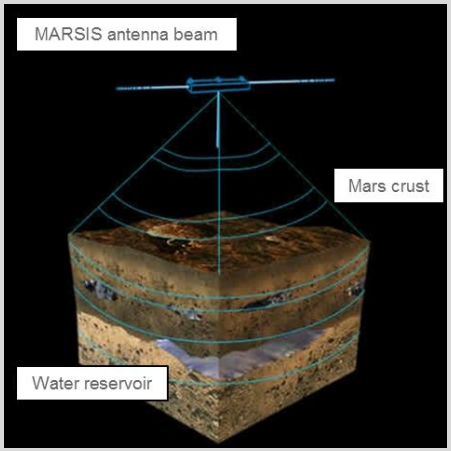


# Enceladus Express Concept - Science Payloads

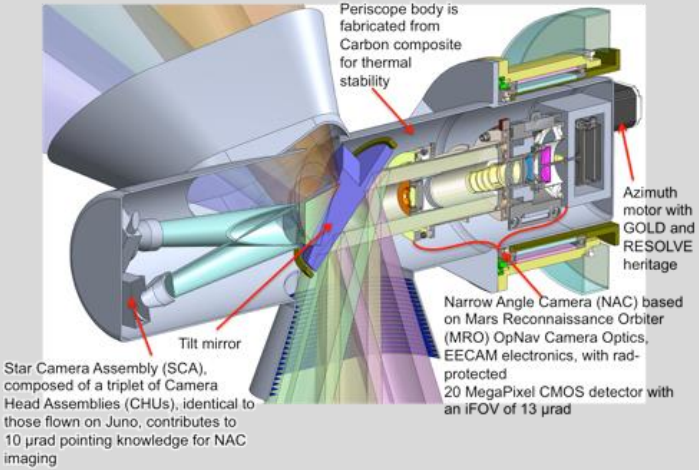
- Spacecraft 1
  - Mass Spectrometer
  - Ice Penetrating Radar
  - ~25 kg total, ~40 W total
- Spacecraft 2
  - Mass Spectrometer
  - Advanced Pointing Imaging Camera
  - ~12 kg total, ~30 W total

Quadropole Mass Spectrometer

Ice Penetrating Radar
(MARSIS ops pictured)




Advanced Pointing Imaging Camera



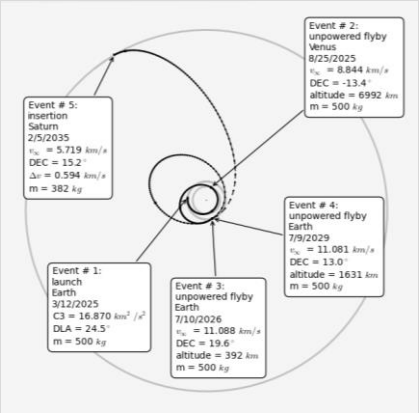
# Enceladus Express Concept - Architectures

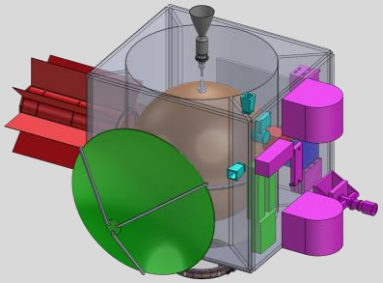
- Case 1: Conventional Chemical Saturn Orbit Insertion
  - 2 Earth and one Venus flybys for gravity assists
  - 1 km/s chemical burn for Saturn Orbit Insertion
  - Saturn close approach will require a close flyby through the ring system, between the F and G rings as Cassini has done

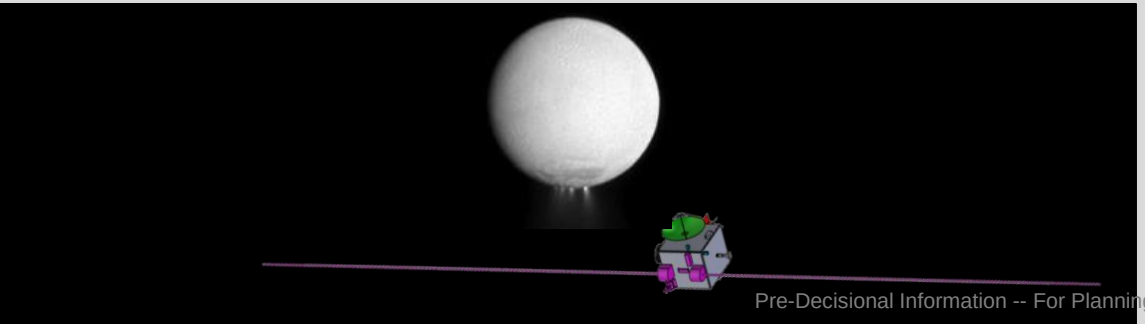
- Case 2: Aerogravity assist at Titan
  - Direct flight to Saturn (requiring a guided upper stage) with upper stage burn (e.g., a Star-48 guided upper stage)
  - Aerobraking and redirection at Titan (same guidance methodology as used by MSL at Mars)
  - Avoids passage through the ring system
  - Transit time shorter by ~2 years

# Enceladus Express Concept – Case 1 Summary

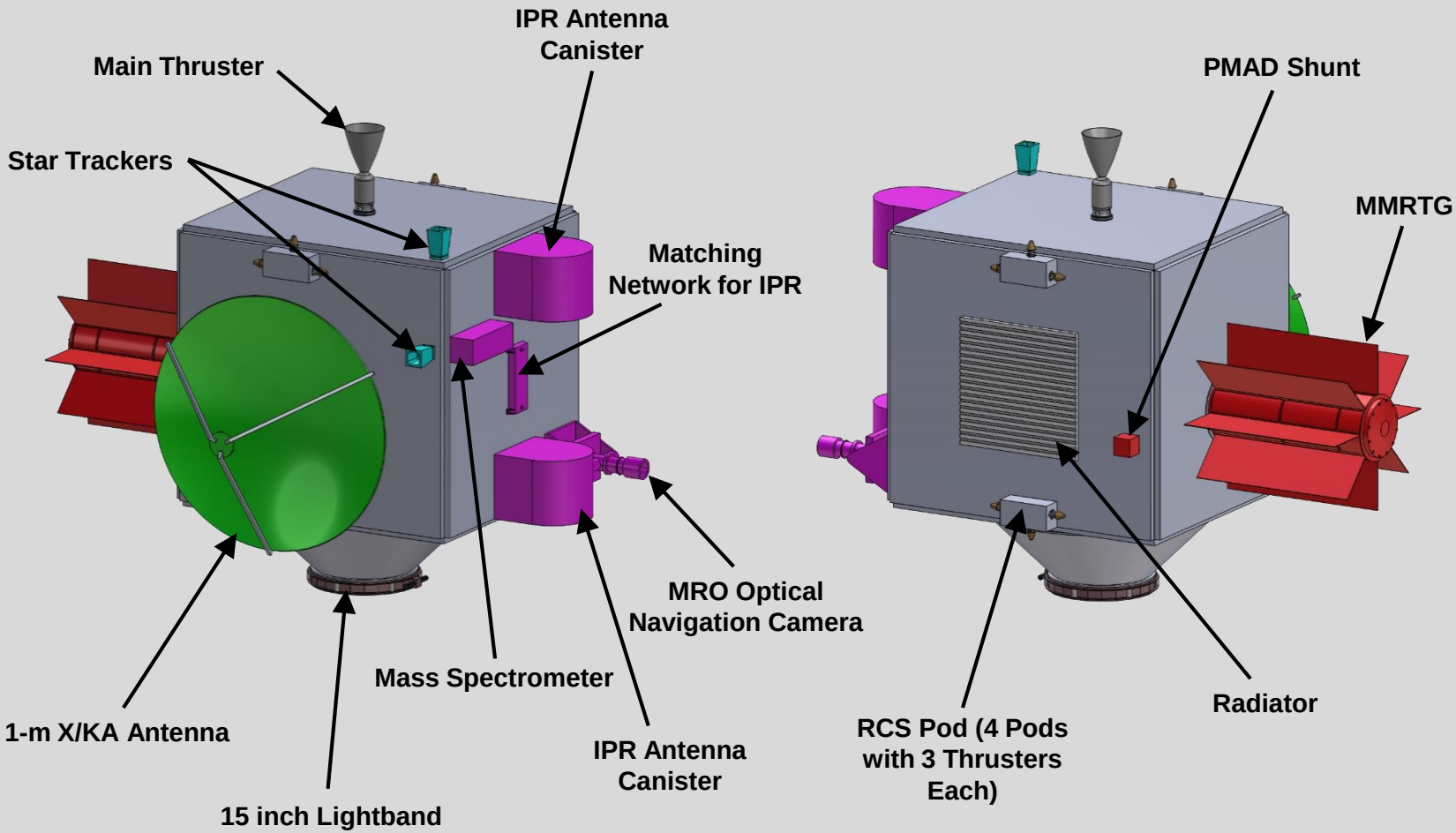
- Mission: Two 450 kg RPS powered SmallSats capture at Saturn and fly through Enceladus plumes 24 times over two years
- Launcher: Atlas 401 to C3 16.8 km^2/s^2
- Science: Habitability and Life, Geoscience(~ 20 kg): Spectrometer, Radar, Imager: 70 Mb (30 Mb compressed) returned every month
- Power (~100W provided by single MMRTG)
  - Single MMRTG sufficient for science and comms (separately) by trickle charging batteries during long, 30 orbits
- Communications - ~ 700 bps Ka-band assuming DSN (34 m)
- AD&CS (IMU, Sun sensors, Startrackers, Cold Gas RCS)
  - Science Collection mode: ~ monthly flyby, 1 hr at a time, 3 axis RCS pointing to 5° accuracy
  - Hibernation during transit: Spun stabilized (3 rpm) pointed to earth
- Propulsion (Hydrazine for all burns)
  - ~ 1 km/s
- C&DH: Radhard Power QUICC, data storage
- Mechanical: Thrust tube design, dual launch platform
- Cost: Dual launch meets New Frontiers cost cap (~ $710M)







# Enceladus Express Concept - External Components



# Power Requirements

- Single MMRTG would provide power to spacecraft : 118 watts@ BOL with a degradation rate of 4.0%
- During Communication Phase the spacecraft requires 146 watts
- MMRTG is providing 44 watts (after losses to bus)-
  - Deficit of 102 watts
- Strategy – use batteries to provide additional power during high power communication phase and recharge during 30 day orbit
- Worst case (greatest energy storage) occurs during Communication Phase at Year 11
- 30 day orbit period consists of
  - Flyby and data acquisition (~35 w-hr defecit)
  - Short duration recharge for flyby (~60 minutes)
  - 8 hour communication to earth (~560 w-hr deficit)
  - Recharge of Battery (~104 hours -4.33 days)
  - Repeat comm/recharge cycle 1 more times

# Case 1 Mission Cost

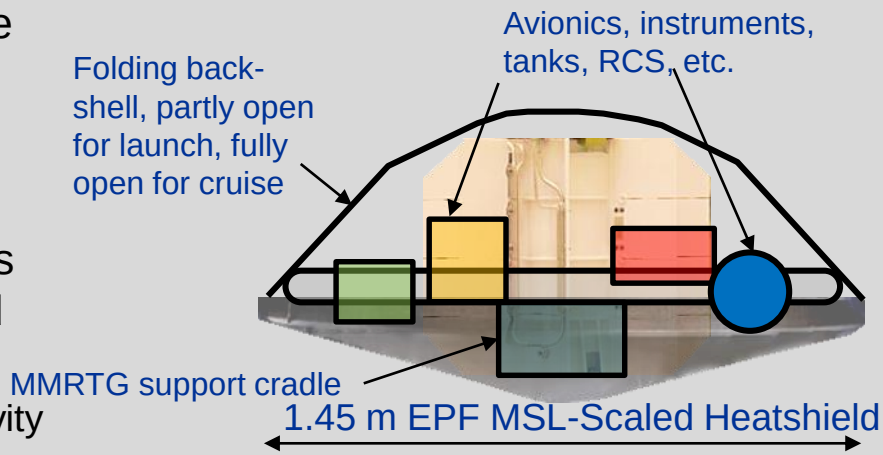
- Total mission cost with 2 SmallSats is within NF Cost Cap
- Uses RPS cost values from the NF 4 AO released on 12/9/2016
- Note this cost is missing Science A-D cost; was not estimated by study

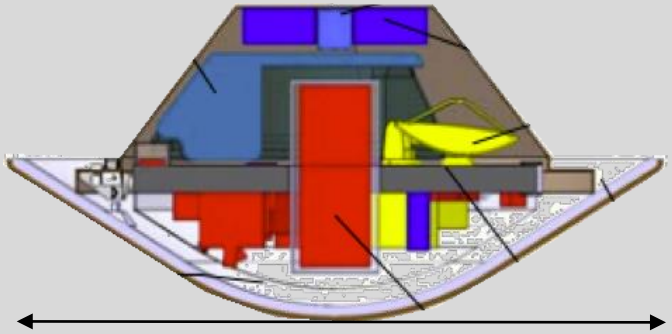
| **Mission Cost Summary** | | |
|---|---|---|
| | | **FY 16$M** |
| Phase A | | 12 |
| 1.0 | Program Management | 38 |
| 2.0 | Systems Engineering | 47 |
| 3.0 | Safety & Mission Assurance | 18 |
| 4.0 | Science | 0 |
| 5.0 | Payload | 89 |
| 6.0 | Spacecraft | 290 |
| *6.1* | *SmallSat A* | 154 |
| *6.2* | *SmallSat B* | 42 |
| *6.3* | *Total RPS-Related Cost* | 94 |
| 7.0 | Mission Operations (LOOS Only) | 12 |
| 8.0 | Launch Vehicle/Services | 13 |
| *8.2* | *Launch Deck* | 13 |
| 9.0 | Ground System | 19 |
| 10.0 | Systems Integration & Testing | 31 |
| 11.0 | Education & Public Outreach | 2 |
| **Total Mission Cost** | | **571** |
| Reserves (25%) | | 143 |
| **Total Cost with Reserves** | | **714** |

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

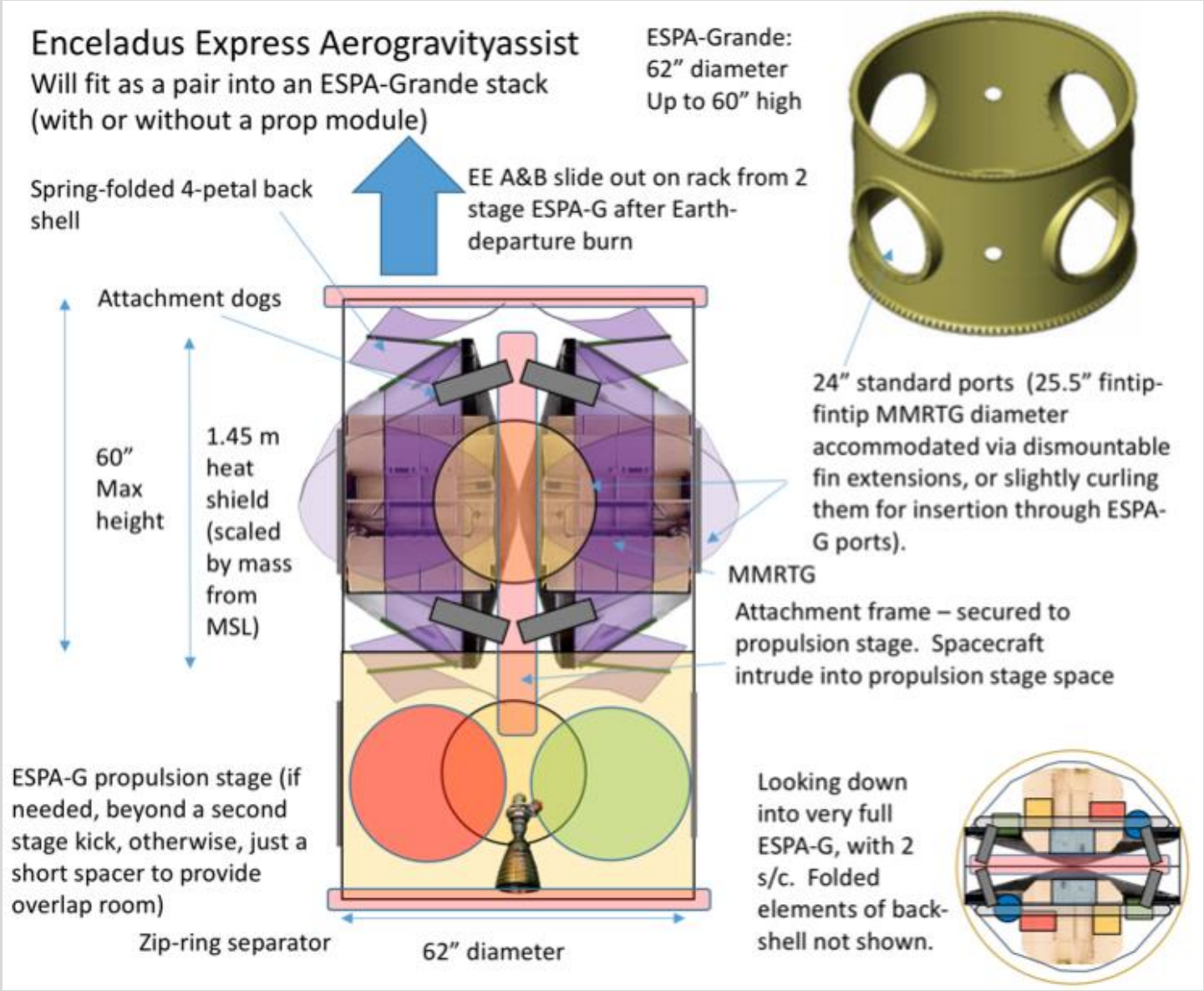
# Case 2 Aerogravity Assist Rough Strawman

- Aerocapture: MSL/Huygens-like architecture (using MSL (or HEEET) shell)
- Science: Same as Case 1
- AD&CS: Startrackers look out of back shell
- Propulsion: Same RCS as Case1 (directions may be limited), vastly lower propellant load than Case 1
  - Hole in backshell to fire RCS during aerogravity assist
- C&DH: Added controls for Aeroshell separation and petals and flyby control
- Thermal:
  - Smaller bus than Case 1
  - Added aeroshell and backshell
  - Water cooling using 3-5 kg water (in tank inside S/C ,with pump)
- Mechanical
  - Smaller bus than chemical s/c
  - Spider holding frame to launch platform



# Case 2 Launch Configuration



# Case 2 Mission Cost

- Total mission cost with 2 SmallSats is within NF Cost Cap
- Uses RPS cost values from the NF 4 AO released on 12/9/2016
- Note this cost is missing Science A-D cost; was not estimated by study

| **Mission Cost Summary** | | |
|---|---|---|
| | | **FY 16$M** |
| Phase A | | 13 |
| 1.0 | Program Management | 39 |
| 2.0 | Systems Engineering | 49 |
| 3.0 | Safety & Mission Assurance | 18 |
| 4.0 | Science | 0 |
| 5.0 | Payload | 89 |
| 6.0 | Spacecraft | 310 |
| *6.1* | *SmallSat A* | 167 |
| *6.2* | *SmallSat B* | 48 |
| *6.3* | *Total RPS-Related Cost* | 94 |
| 7.0 | Mission Operations (LOOS Only) | 13 |
| 8.0 | Launch Vehicle/Services | 97 |
| *8.1* | *Launch Vehicle (charge for high performance launch and upperstage)* | 85 |
| *8.2* | *Launch Deck* | 13 |
| 9.0 | Ground System | 19 |
| 10.0 | Systems Integration & Testing | 32 |
| 11.0 | Education & Public Outreach | 2 |
| **Total Mission Cost** | | **682** |
| Reserves (25%) | | 149 |
| **Total Cost with Reserves** | | **832** |

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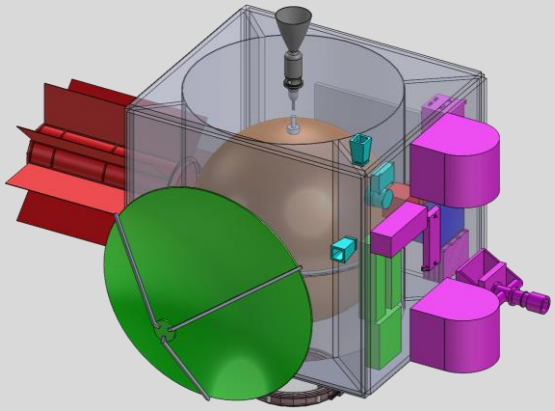
# Top-Level Case Comparison

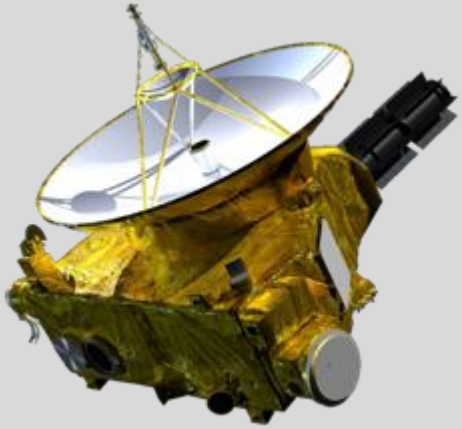
| Parameter | Case 1 Monoprop | Case 2 Aerogravity Assist |
|---|---|---|
| Launch/Arrival Date | VEEGA 2025/2035 | Direct 2026/2031 |
| Launcher | Atlas 401 (w 50% margin): free for NF | Atlas 551/Star 48: Adds $85M |
| S/C Mass | 250 kg dry [~200 kg propellant] | 210 kg dry (includes 26 kg aerosystem) [~30 kg propellant] |
| Mission Cost | ~$710M | ~$830M |
| Readiness | Off-the-shelf | Aerogravity assist system needs adaptation from Mars case |
| Operations | 11 year cruise / 2 yr science<br>(~$20M add'l cruise cost) | 5 year cruise / 1 yr science |
| Science Complete | 2038 | 2036 |
| Pros | Lower cost | Much shorter cruise and science phase, 2 year earlier science. |
| Cons | Longer cruise/ops (13 yrs), 2 year later science, Earth flybys (w/ RPS), Risky Saturn flyby (inside rings) | More expensive launcher, aerogravity maneuver (same as MSL), more complex/expensive S/C with aerosystem? |

# Comparison with Past 'Small' Interplanetary Spacecraft

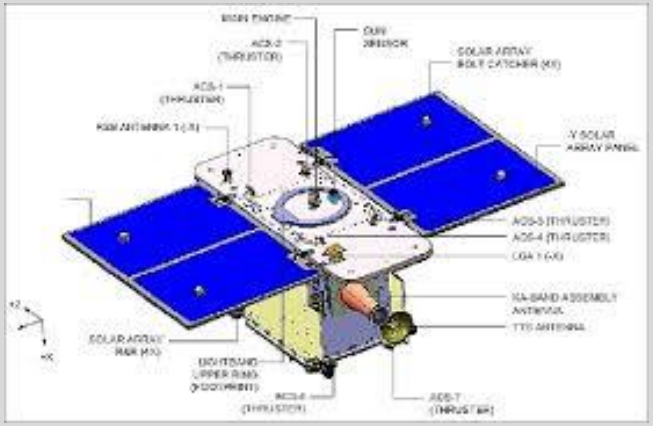
- New Horizons (~$700M): Wet 478 kg / Dry 401 kg / MonoProp 77 kg Payload 30 kg / 200 $W_e$ power @ 9 years (LV: Atlas 551 with a Star48)
- Grail (~$500M): 2 spacecraft each Wet 307 kg/ Dry 201 kg/ MonoPropellant 106 kg / 700 $W_e$ power
- LADEE ($280M): Wet 383 kg / Dry 248 kg / Payload 20 kg / 135kg Propellant (biprop) / ~100 $W_e$ power
- Enceladus Express Case 1 (~$700M): 2 spacecraft each Wet ~450 kg / Dry ~250 kg / ~100 $W_e$ power
- Enceladus Express Case 2 (~$800M): 2 spacecraft each Wet ~250 kg / Dry ~200 kg / ~100 $W_e$ power



Enceladus Express



New Horizons



Grail

LADEE

# Technical and Cost Lessons Learned (1)

- A single MMRTG does have sufficient power for a SmallSat IF major events (<day) (science, propulsion, communications) can be supplemented using trickle charged battery power (charged during long periods of non-events ~ 10s of days)
  - Enabled by the Spacecraft 'low-power' mode
- A single MMRTG powered spacecraft, even carrying significant $\Delta V$ (~ 1 km/s) and 20 kg of science instrumentation, fits in the SmallSat class (<500 kg)
- Launching two identical, zero fault-tolerant spacecraft provides a method of risk reduction for flybys through Enceladus' plumes
  - An alternative approach using two MMRTGs on one single fault-tolerant spacecraft may or may not provide a cheaper alternative – further work is needed
  - However, a larger dual-string s/c would no longer be a strawman SmallSat solution for other missions

# Technical and Cost Lessons Learned (2)

- An approach using aerogravity assist can reduce propellant mass dramatically on the SmallSat but requires an aeroshell system and added risks
  - Aerogravity assist vehicle also delivers science ~1-2 years earlier but costs more, costs that are at least in part compensated by a much reduced mission length
  - This analysis needs further refinement

# Study RPS Findings

- RPS SmallSats of 250-500 kg were shown to be feasible.
  - MMRTG can meet the requirements for the mission profile during its 11 year duration
- Spacecraft had EOM power needs of 33 $W_e$ in low-power recharge mode.
  - Small variations in minimum power phase (i.e battery recharge) can lead to greatly increased recharge time
  - Increasing min spacecraft power to 41 $W_e$ prevents power system from closing
- The designed SmallSat concepts were constrained in both mass and power.
  - Mass, dimensions, and cost of the power system pushed the design away from CubeSat to larger, traditional spacecraft components.
  - The high propellant masses and large tank for conventional propulsion made a spacecraft design centered around the MMRTG impractical.
- Use of advanced, smaller RPS could make these mission concepts more compelling since the mass and power degradation of MMRTG became a challenge.
  - If the MMRTG degradation rate is increased from 4% to 5%, the mission doesn't close
  - Higher power would enable higher data return, and lower risk in low power modes
- An REP architecture was investigated, but study determined that spacecraft could not produce enough thrust for EP with one MMRTG
  - REP, if feasible, could lead to lower propellant mass, smaller propellant tanks, and a smaller spacecraft bus

# Conclusions

- Currently available RPS systems (MMRTGs) and their potential improved version (eMMRTGS) are potentially enabling for a wide range of very aggressive but yet economical SmallSat science missions into the outer solar system
  - *As a result, mission designers <u>today</u> can propose small, economical but scientifically important science missions that would be otherwise impossible without RPS*

- Enceladus was chosen as a study target because of its very intriguing internal dynamics that are incongruously and mysteriously keeping an internal ocean active and even venting liquid water – offering the opportunity to test for life processes without landing
  - RPS would keep an Enceladus mission small and lightweight, able to traverse the plumes with low risk compared to solar-powered missions
  - The mission design is applicable as a generic platform for a wider range of outer planets SmallSats
  - Two forms of this mission were studied, a conventional SOI mission (Case 1), and a lower mass aerogravity assist option (Case 2)
  - If Atlas is unavailable, the Falcon Heavy could economically carry both of these cases on ESPA-Grande accommodation
    - For Case 2 (aerogravity assist), the spacecraft could fit inside the adapter ring
  - Both cases potentially fit into the NF cost cap

- Substantial improved performance of current RPS with similar or less mass but higher specific power could enable an REP version of the Enceladus Express SmallSat mission concept, but with a lower spacecraft mass (e.g. 100-200 kg fully loaded)
  - Such a spacecraft would have powerful applicability to a wide range of outer Solar System missions

# Questions?