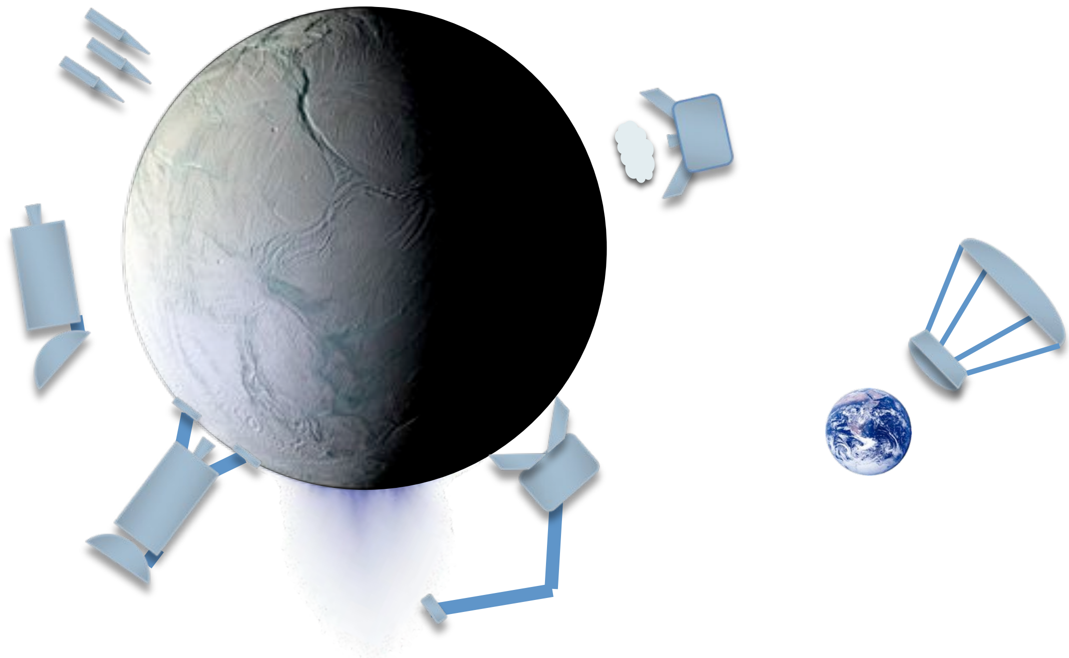

Mission Architecture Options For Enceladus Exploration

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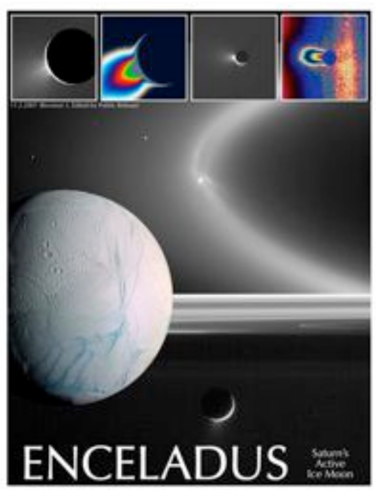
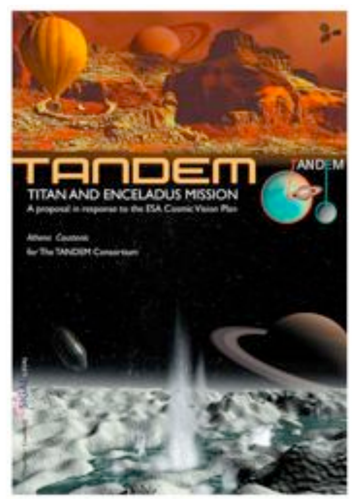
Past Enceladus Studies

- 2006 GSFC NASA Academy EAGLE Study
- 2006 NASA "Billion Dollar Box" Study [Refs 1,2]
- 2007 NASA Enceladus Flagship Study [Ref 3]
- 2007 ESA Titan and Enceladus Mission (TandEM) [Ref 4]
- 2007 JPL Enceladus RMA Study [Ref 5]
- 2008 NASA/ESA Titan Saturn System Mission (TSSM) [Ref 6]





Pre-decisional, for planning and discussion purposes only.

Enceladus Science Questions

- Summary of Enceladus Science Questions from past studies:
  - Does Enceladus provide (or has provided in the past) the conditions necessary (or sufficient) to sustain biotic or pre-biotic chemistry?
  - What is the heat source; what drives the plume?
  - What is the temporal variability of the plume?
  - What is the internal structure, mass distribution, and gravity field of Enceladus?
  - Is there sub-surface liquid water; if so, what is its depth, extension, and composition?
  - What is the surface composition and morphology of Encleadus?
  - What is the internal structure and composition of the plume?
  - What are the interaction effects of the plume on the Saturnian system and Titan?
  - Does the composition of Enceladus and/or the existence of the plume give us clues to the origin and evolution of the solar system?

Past and Future Cassini Investigations

23 Enceladus Flybys with the Cassini instrument suite sets a high bar for any future Enceladus mission

Saturn Orbiter Missions to Enceladus

- Traditional Titan-Driven Tours
  - 10-20 Enceladus flybys per year at speeds of 4 km/s or higher
  - Titan-Enceladus cycler tours could reduce operational complexity
  - Conducive to addition of Titan and Saturn system science
- Leveraging Icy Satellite Tours
  - ~2 years needed before Enceladus for Flybys of Rhea, Dione, and Tethys
  - 50 or more Enceladus flybys per year at speeds ~1 km/s
- Plume Sample Return
  - Sample return missions that collect samples from Saturn orbit are most attractive
  - Multiple samples of the plume and E-ring can be collected at speeds of 3-4.5 km/s and returned to Earth for study

Enceladus Orbiters

- Until recently, astrodynamics techniques have not been sufficient to enable an Enceladus orbiter.
- New "Leveraging Tour" techniques allow a TSSM-sized orbiter to reach Enceladus with a ~2.5 year flight time from SOI (~11-12 year flight time from Launch) [Ref 7]
- New techniques from Frozen Orbit Theory and Circulating Eccentric Orbits (e.g. the JSO Ball-of-Yarn) can be used do design long term stable orbits at inclinations as high as 65°. [Ref 8]
  - Navigation issues remain to be resolved to enable these orbits fly directly through the plume
  - Brief excursions from stable orbits into unstable plume-crossing orbits are possible fro a cost of ~100 m/s
  - Low speed flybys prior to orbit insertion could also be used for in situ plume observations
  - These long term stable orbits demonstrate good observablity for detecting a sub-surface ocean. [Ref 9]

Enceladus Surface Science

- Penetrators and Hard Landers
  - Are attractive for delivery from Saturn tour (e.g. TandEM)
  - Many technical challenges must be overcome. There are difficulties in the design of airless body penetrators and many uncertainties about the surface properties at the point of impact.
- Soft Landers
  - The main challenge, is getting the lander to Enceladus orbit. From that point it is relatively easy to land. (That is, its "easy" compared to other airless body landings.)
  - After landing, Enceladus' low gravity makes mobility by "hopping" attractive. Hopping can be achieved by thrusting or possibly even springs.
- Orbilanders
  - An "orbilander" is a spacecraft that orbits and then lands
  - Orbilanders are an option to do both orbital science and surface science with one vehicle.

Multi-Moon Orbiters

- Orbit Titan and Enceladus with one spacecraft
  - Recent development of new v-infinity leveraging techniques suggests that it may be possible to transfer between Titan and Enceladus orbit via n-body effects and moderate-sized maneuvers [Refs 7,10]
  - Back of the envelope estimates suggest that something TSSM-sized (but possibly without in situ elements) could orbit both moons in a 14 year mission
  - More research into this concept is needed to bring it to the maturity of the concepts previously presented

Example: 2007 RMA Architectures

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Example: 2007 RMA Designs

- All RMA architectures required Titan aerogravity assists. New astrodynamics techniques developed since 2007 would enable many of the architectures below without Titan aerogravity assists.
- Similar new developments may also enable additional architectures not considered in this study. (e.g. plume sample return)

Upcoming Trajectory Opportunities

- Jupiter flybys provide quick trajectories to Saturn every ~19 years (7-8 year length instead of 9-10 yr)
  - The next Jupiter opportunities happen 2014-2019 (However the 2018-2019 opportunities are only useful to spacecraft under ~1000 kg. After that, the next opportunities happen in the mid 2030s.
- However 9-10 yr flight time trajectories recur roughly every 1.5 years
  - A Solar Electric Propulsion (SEP) boost stage can be used to take ~2 years off of this flight time

Findings

- Enceladus orbiters and landers are both feasible
- Other novel missions (plume sample return and leveraging tour) are also possible
- Tremendous progress has been made in developing Enceladus mission concepts since the discovery of the plumes in 2005.
- We should continue to study Enceladus missions and see what more this creative energy can do for us.

- **Recommendation**
  - ***The 2007 RMA Enceladus study should be updated to take advantage of newly developed astrodynamics techniques***

References

1. T.R. Spilker, K.R. Reh, J.O. Elliott, R.D. Lorenz, and J.R. Spencer, "The "Billion Dollar Box" Study of Science Missions to Saturnian Satellites," IEEEAC paper #1095, 2008 IEEE Aerospace conference, 1-8 March 2008.
2. K. Reh, J. Elliott, T. Spilker, E. Jorgensen, J. Spencer, and R. Lorenz, "Titan and Enceladus $1B Mission Feasibility Study Report," JPL publication D-37401, Jan 30, 2007.
3. NASA Enceladus Flagship Study Report, NASA Goddard Space Flight Center, 2007 (http://opfm.jpl.nasa.gov/library/)
4. A. Coustenis et al., "TandEM: Titan and Enceladus Mission," Experimental Astronomy, Volume 23, Issue 3, pp. 893-946.
5. T.R. Spilker, R.C. Moeller, C.S. Borden, W.D. Smythe, R.E. Lock, J.O. Elliott, J.A. Wertz, N.J. Strange, "Analysis of Architectures for the Scientific Exploration of Enceladus," IEEEAC paper #1644, 2009 IEEE Aerospace conference, 7-14 March 2009.
6. "Titan Saturn System Mission Final Report on the NASA Contribution to a Joint Mission with ESA," Jet Propulsion Laboratory, 2009. (http://opfm.jpl.nasa.gov/library/)
7. N.J. Strange, S. Campagnola, and R.P. Russell, "Leveraging flybys of Low Mass Moons to Enable an Enceladus Orbiter," AAS Paper 09-435, AAS/AIAA Astrodynamics Specialists' Conference, Pittsburgh, PA, Aug. 2009.
8. R.P. Russell and M.P. Lara, "On the Design of an Enceladus Science Orbit," Acta Astronautica, V. 65, No. 1-2, p. 27-39.
9. Casotto, S., Padovani, S., Russell, R.P., Lara, M., "Detecting a Subsurface Ocean from Periodic Orbits at Enceladus," Poster P23B-1366, AGU 2008 Fall Meeting, 15-19 December 2008, San Francisco, CA.
10. S. Campagnola and R.P. Russell, "The Endgame Problem Part A: V-Infinity Leveraging Technique and The leveraging Graph," AAS Paper 09-224, AAS Space Flight Mechanics Meeting, Savannah, GA, Feb. 2009.