National Aeronautics and Space Administration

Low Thrust Trajectory Design Techniques for Enceladus Lander

Principal Investigator: Damon Landau (312)
Stefano Campagnola (392), Reza Karimi (392), Nathan Strange (394)

Program: Spontaneous Concept

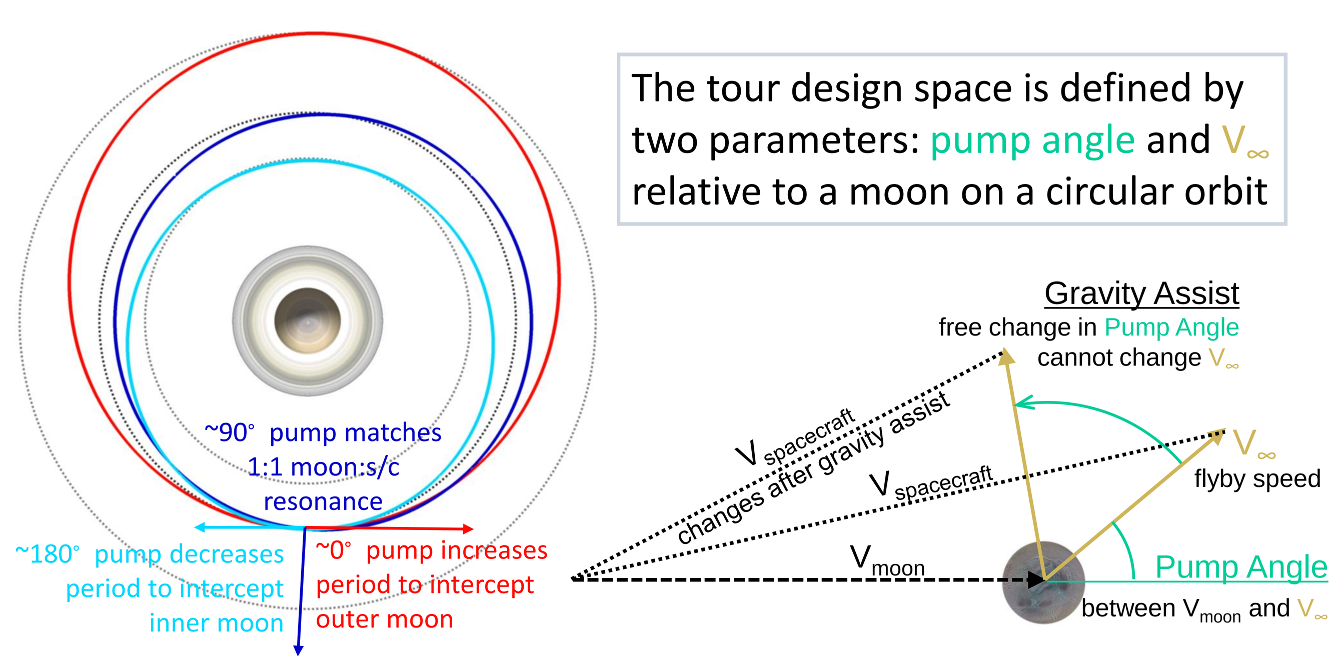
Project Objectives:
- We generate electric propulsion (EP) satellite tours at Saturn that deliver unprecedented mass to Enceladus
- The state of the art sought high-thrust tours by hand, resulting in insufficient mass and unwieldy design cycles
- Our technique automates the production of optimal low-thrust tours in a time-efficient manner necessary for formulation feasibility studies
- The method is general and applicable to any Ocean World

FY18/19 Results:
- Linearized optimal control theory improves super-computing state of the art by two orders of magnitude in compute time
- Automated tour design via Dynamic Programming relieves time burden of trial & error approaches
- Proof-of-concept tour (below) exceeds two tons to the surface of Enceladus with near-term EP without SLS launch

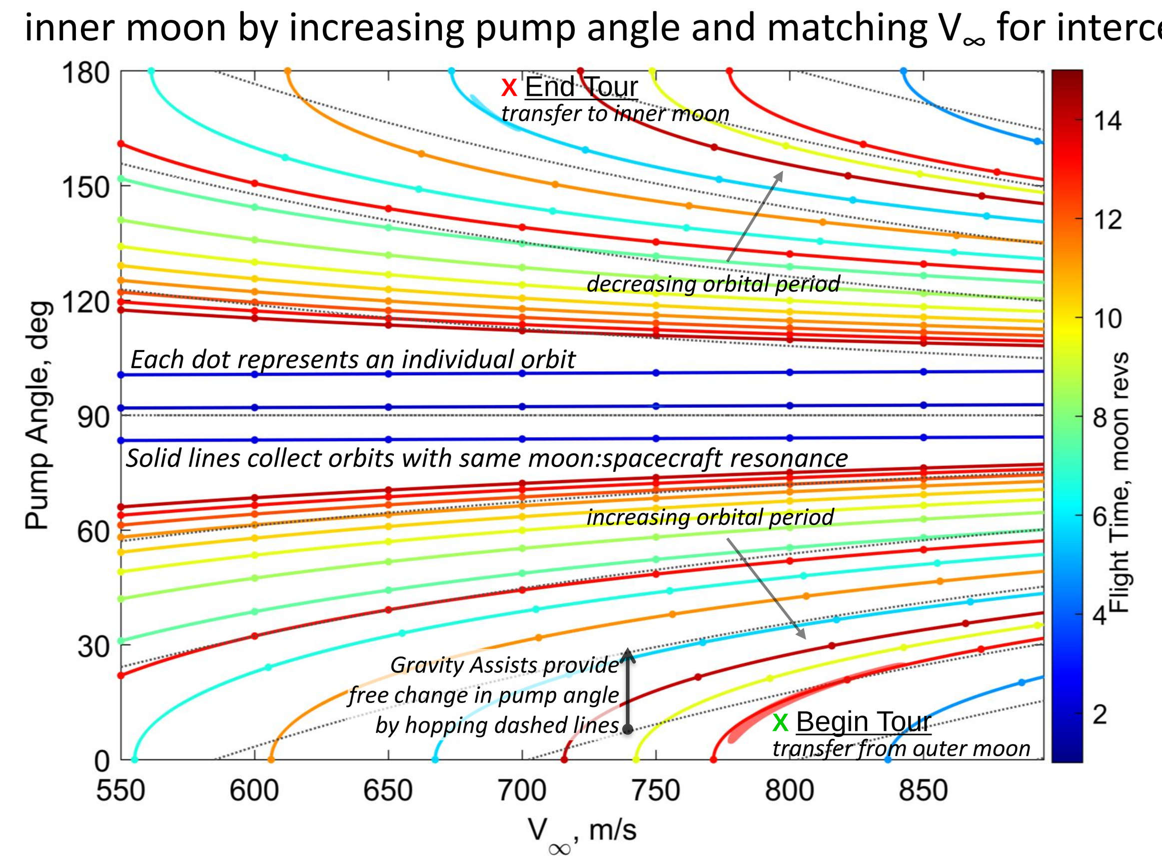
Benefits to NASA and JPL:
- Reduces demand on design teams with automated path optimization and efficient computation of low-thrust transfers
- Introduces a branch to the trajectory toolkit that combines EP with dozens of satellite gravity assists
- Increases landed mass by an order of magnitude at Ocean Worlds providing a *necessary* step to reach the ocean of Enceladus

Step 1: Sample Orbital State Space

The tour design space is defined by two parameters: pump angle and V_∞ relative to a moon on a circular orbit

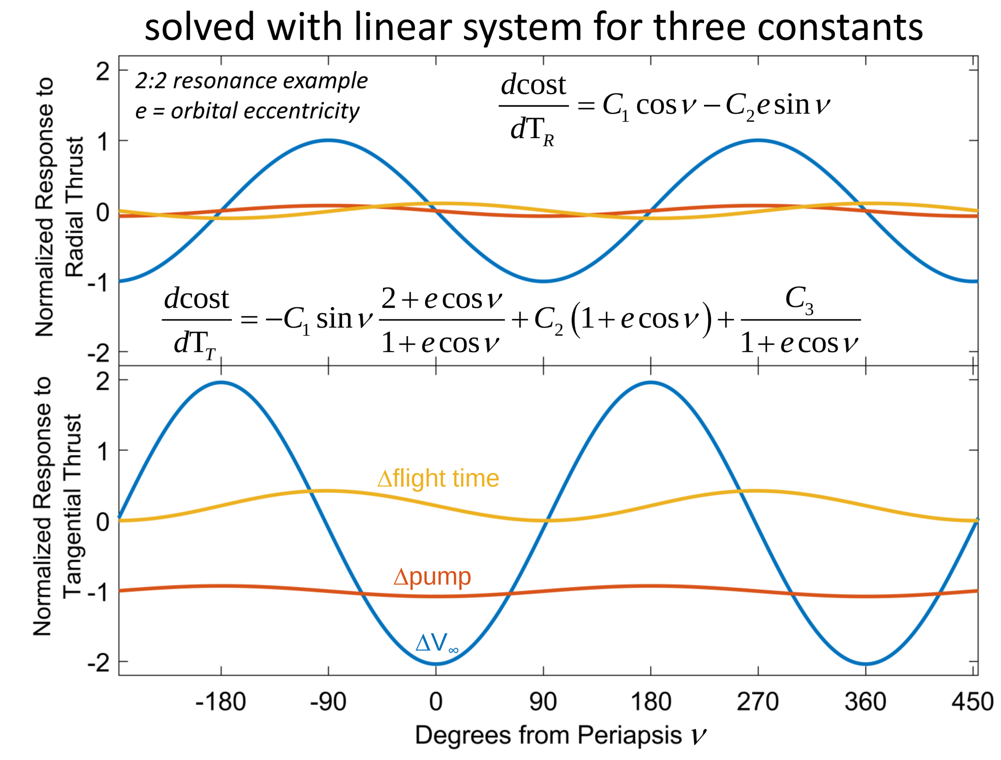


Satellite tours decrease orbital period from previous outer moon to next inner moon by increasing pump angle and matching V_∞ for intercept



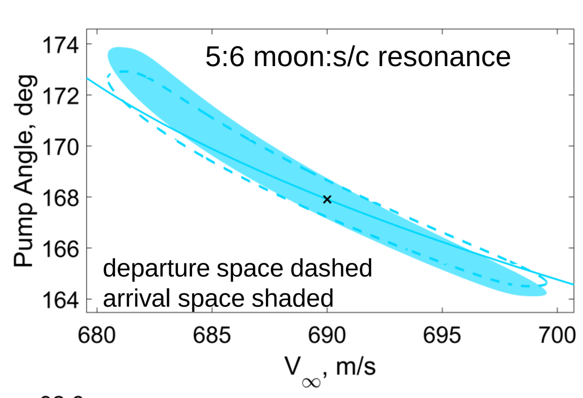
Step 2: Apply Optimal Low Thrust

Optimal low-thrust control and state response solved with linear system for three constants

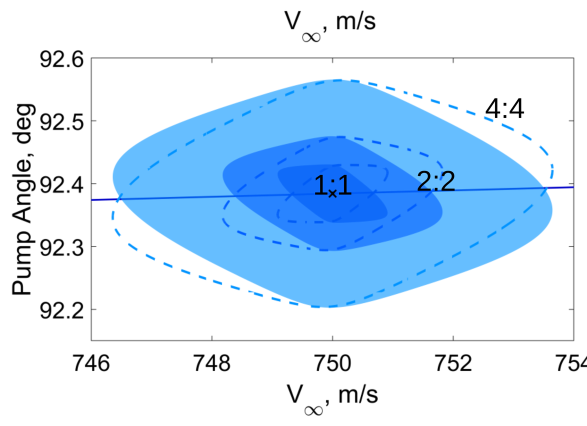


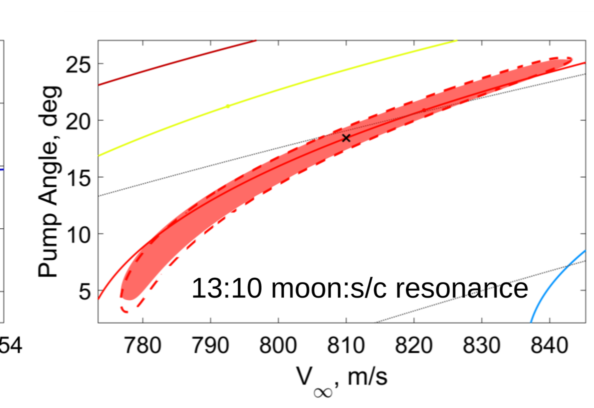
$$\frac{d\text{cost}}{dT_R} = C_1 \cos\nu - C_2 e \sin\nu$$

$$\frac{d\text{cost}}{dT_T} = -C_1 \sin\nu \frac{2+e\cos\nu}{1+e\cos\nu} + C_2(1+e\cos\nu) + \frac{C_3}{1+e\cos\nu}$$



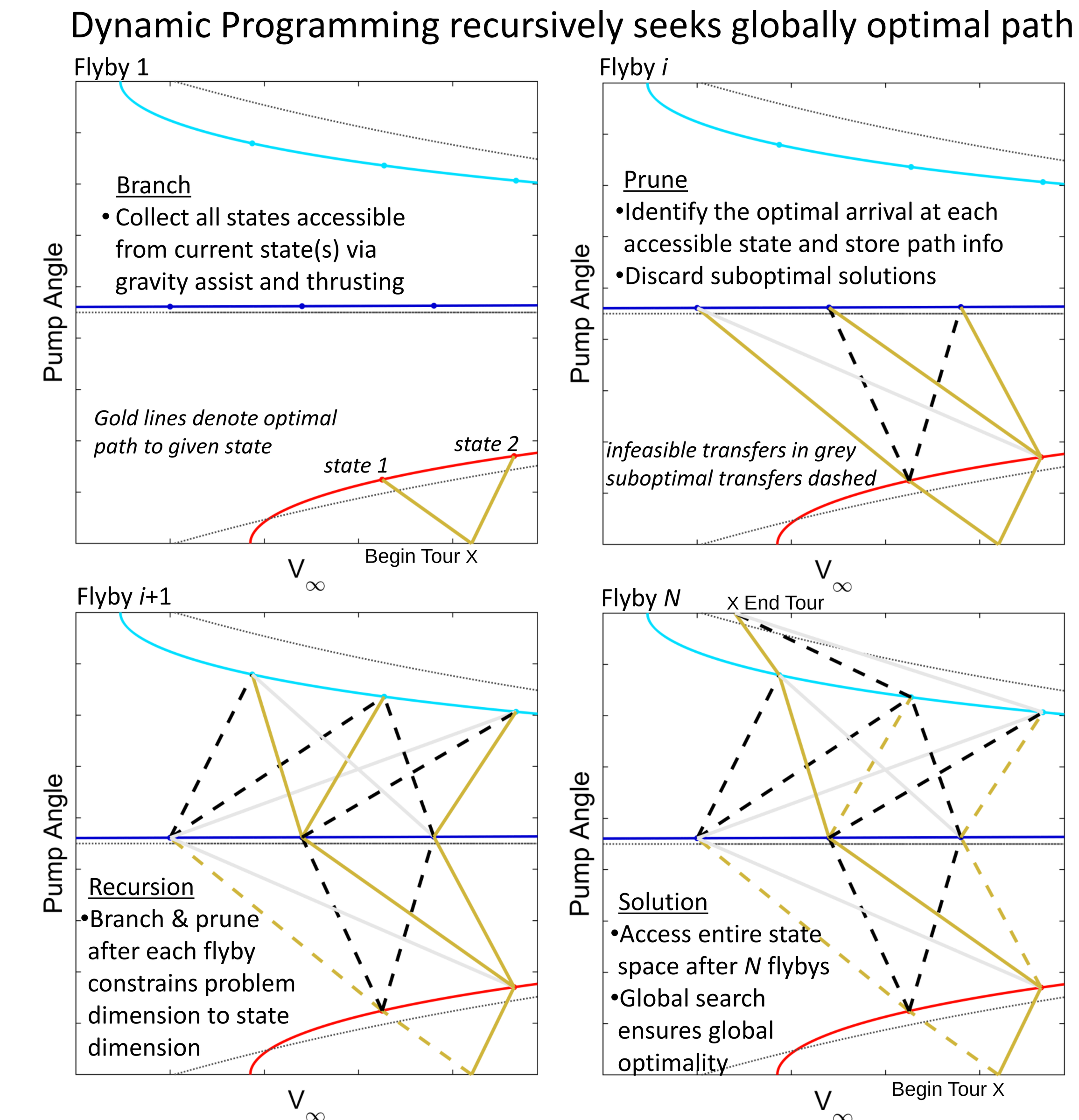
- Low thrust is treated as a perturbation to conic orbits
- Analytic dynamics and control equations available
- Thrust moves spacecraft through pump/V_∞ space.



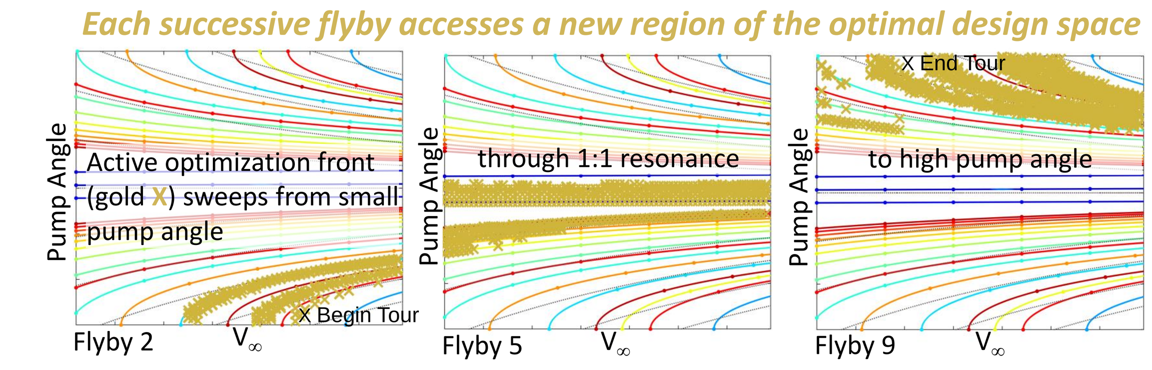


Step 3: Connect Orbits to Create Tours

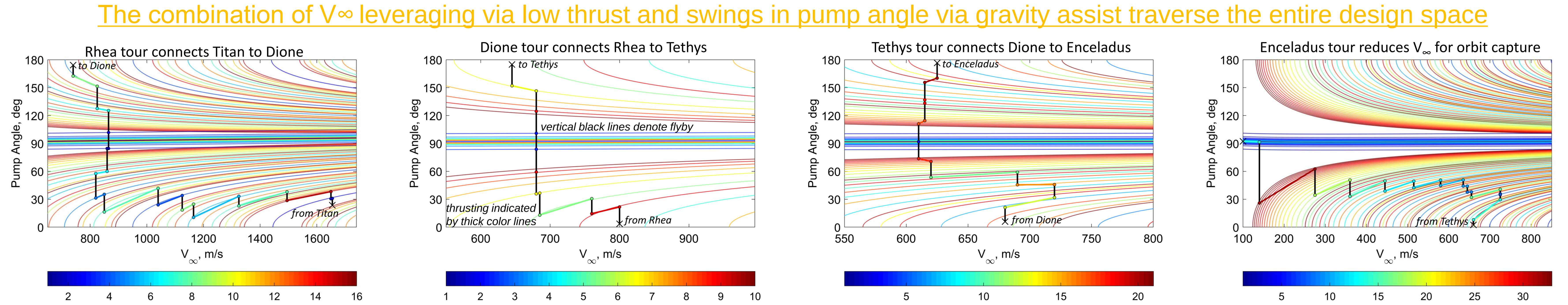
Dynamic Programming recursively seeks globally optimal path

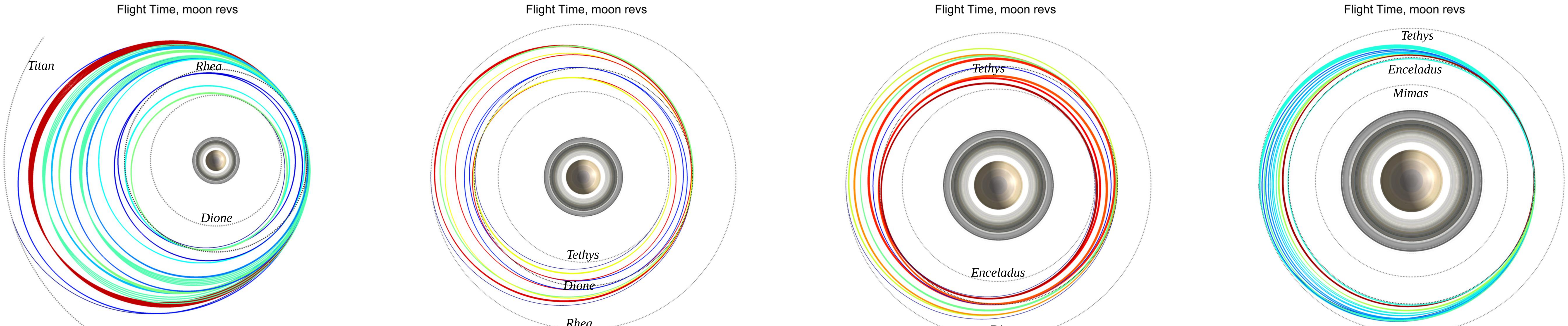


Each successive flyby accesses a new region of the optimal design space



The combination of V∞ leveraging via low thrust and swings in pump angle via gravity assist traverse the entire design space





- Low-thrust tour from Titan delivers 2200 kg to the surface of Enceladus in 2.5 years with 1.5 kW EP system.
- The combination of EP with multiple gravity assists reduces tour propellant by a factor of 14.
- This tour comprises 14 flybys of Rhea, 9 flybys of Dione, 9 flybys of Tethys, and 12 flybys of Enceladus.

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

PI Contact Information: damonlandau@jpl.nasa.gov (818) 354-2205

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