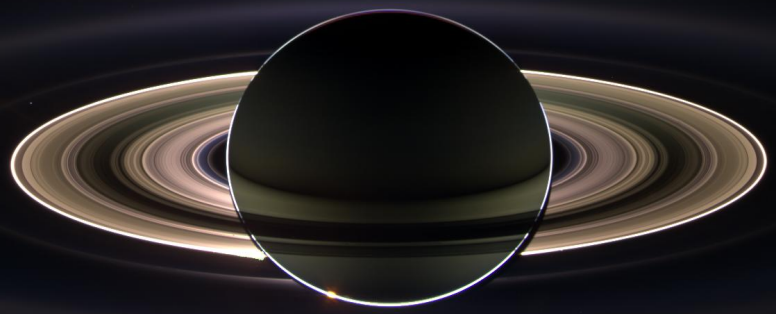
Cassini Maneuver Experience Through the Last Icy Satellite Targeted Flybys of the Mission

AAS 16-243



Sonia Hernandez

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Jet Propulsion Laboratory

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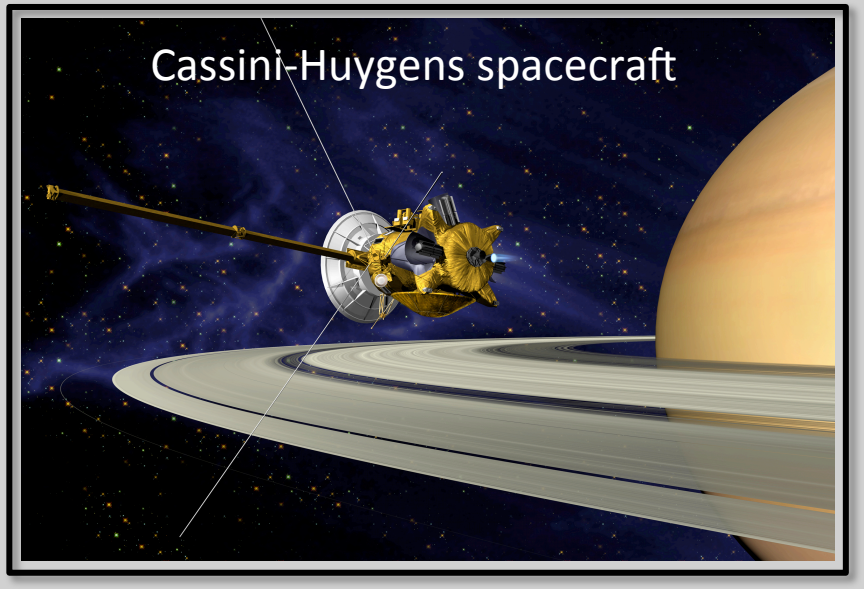
Mission Overview

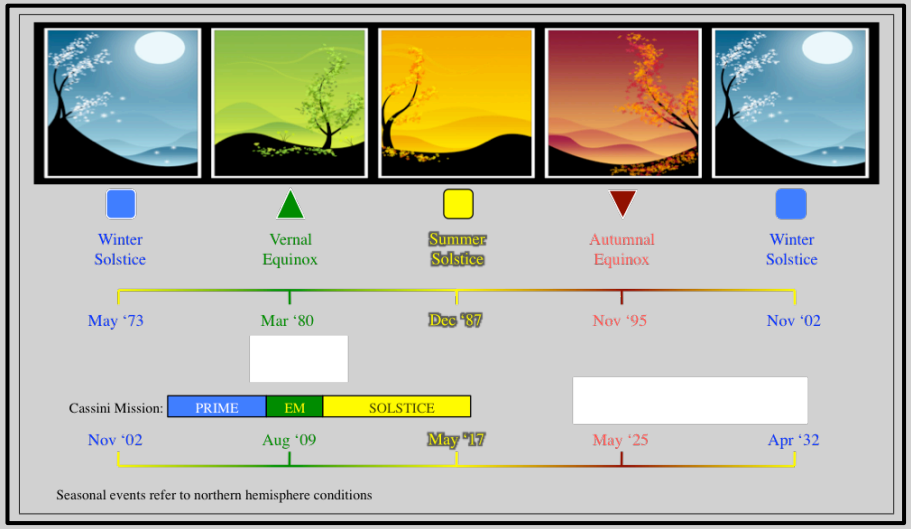
Launched in 1997

Arrived at Saturn in 2004

Saturn Tour:

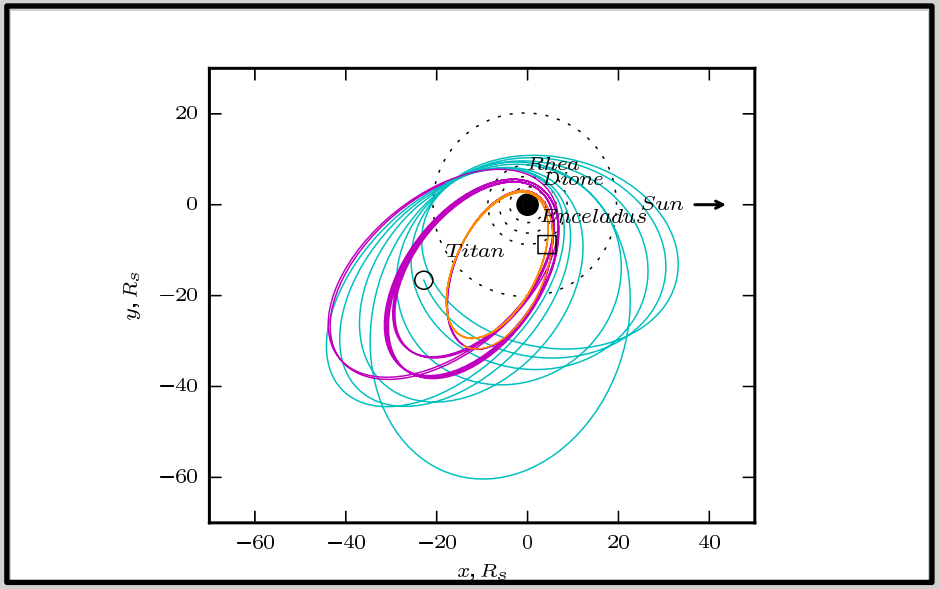
- 4-year Prime Mission (2004 – 2008)
- 2-year Equinox Mission (2008 – 2010)
- 7-year Solstice Mission (2010 – 2017)

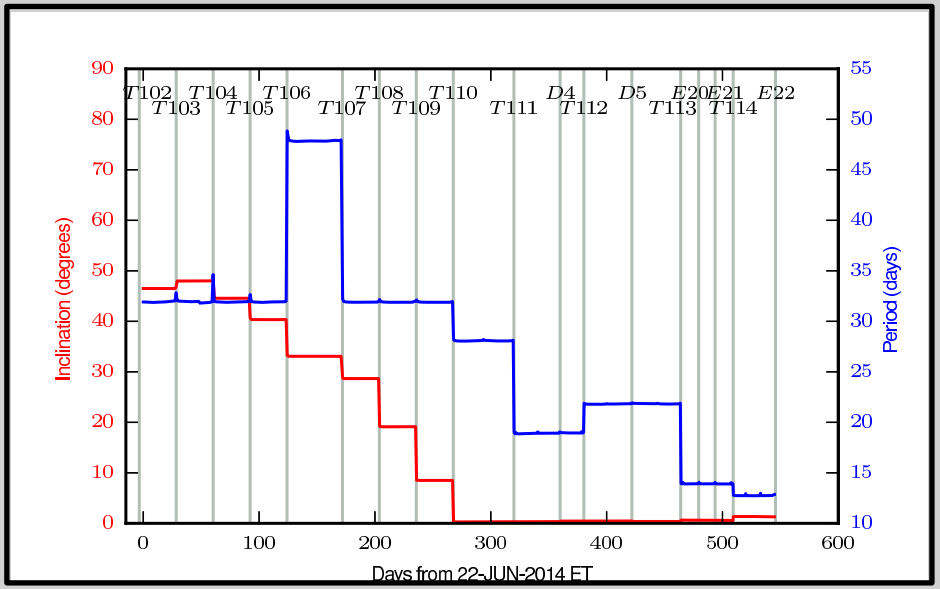




Prime and Equinox Missions	Solstice Mission
6 years	7 years
90 encounters	70 encounters
139 revs	132 revs
269 maneuvers	205 maneuvers
600 m/s	**147 m/s**

Solstice Mission: 5th Year





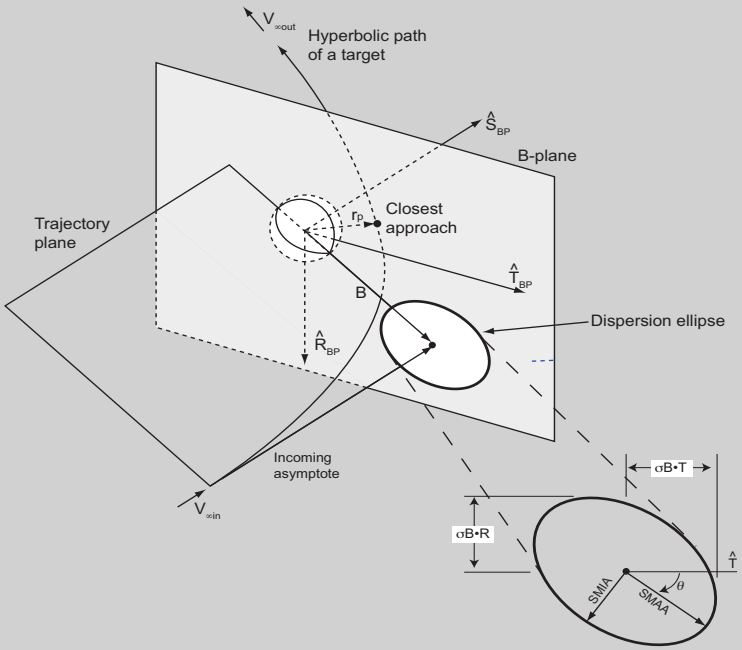
Trajectory from June 2014 – December 2015

- **End of Second Inclined Phase (In-2)**
  - T102-T103: Titan occultation for atmospheric studies of southern polar regions
  - T104-T109: Low altitude flybys at high northern latitudes around lakes region
- **Second Equatorial Phase (Eq-2):**
  - T110-T113
  - D4, D5: Gravity measurements to determine if Dione is geologically active
  - E20, E21: Closest targeted flyby to Enceladus' plume in southern region
- **Beginning of Third Inclined Phase (In-3)**
  - T114 increased inclination to set up E22 flyby (last icy satellite targeted flyby of mission)

17 satellite encounters:

12 Titan, 2 Dione, 3 Enceladus

B-plane Targeting

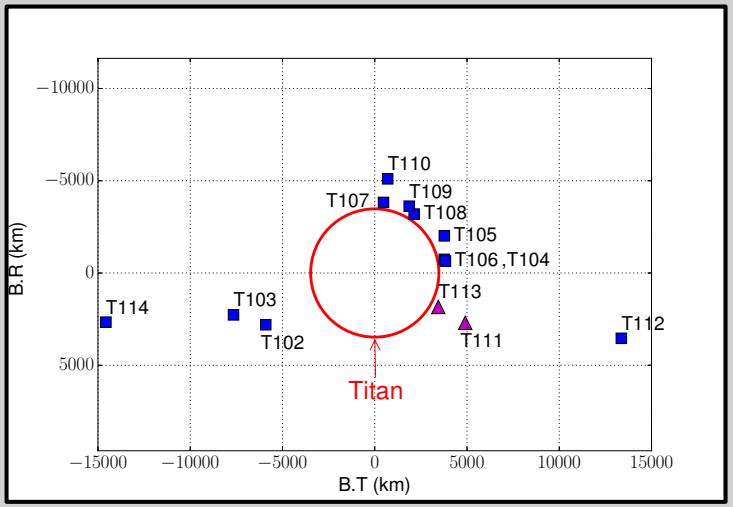


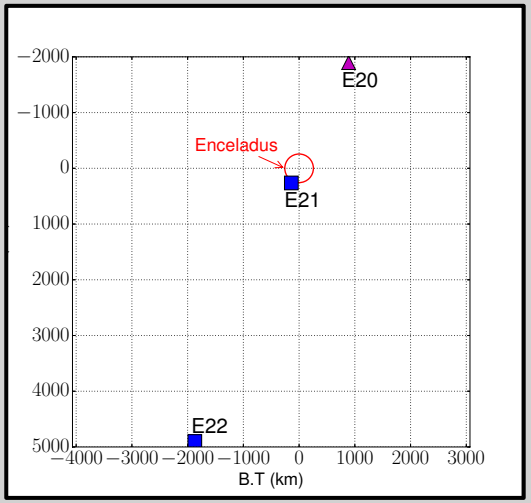
B-plane: normal to the incoming asymptote of hyperboblic orbit ($\mathbf{v}_\infty$) and contains the target body center of mass.

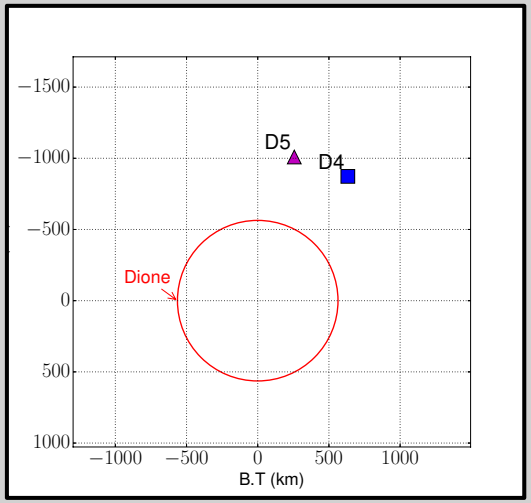
B-vector: Vector from center of mass to the point where $\mathbf{v}_\infty$ intersects B-plane

$$\left.\begin{array}{l}\mathbf{B}\cdot\mathbf{R}\\ \mathbf{B}\cdot\mathbf{T}\end{array}\right\}\text{ B-vector components in B-plane}$$

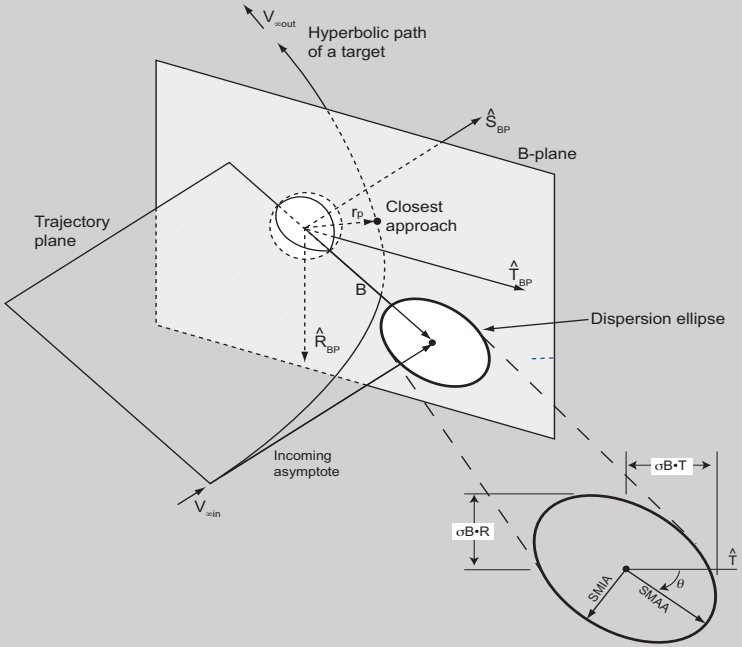
$$\left.TF\right\}\text{ Flyby time if B-vector were zero (linearized time-of-flight)}$$







B-plane Targeting



$$\mathbf{\Delta B} = \begin{bmatrix} \Delta \mathbf{B} \cdot \mathbf{R} \\ \Delta \mathbf{B} \cdot \mathbf{T} \\ \Delta TF \end{bmatrix}$$

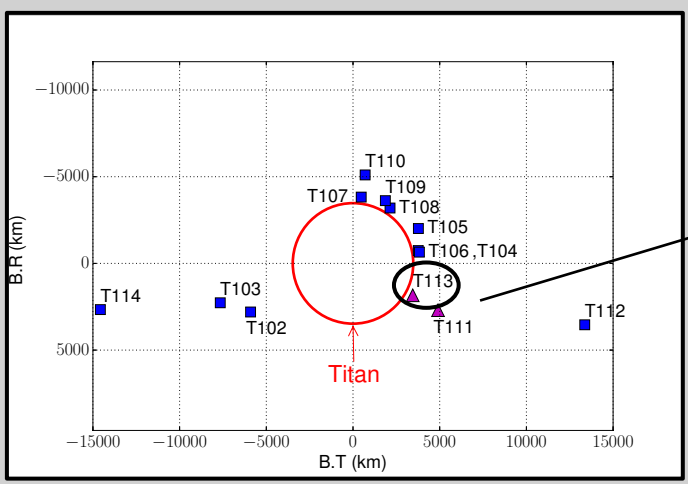
B-plane miss parameters perpendicular to $\mathbf{v}_\infty$

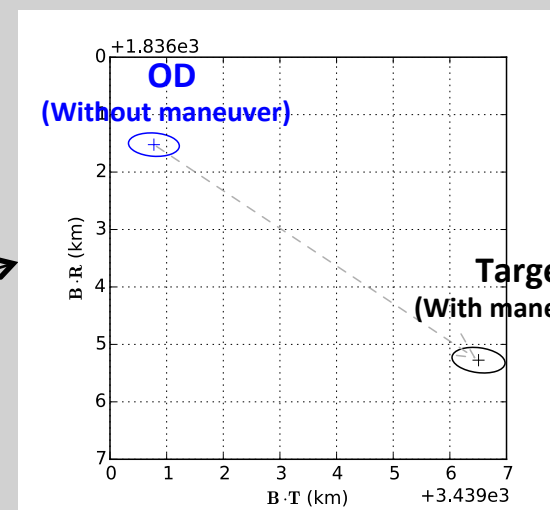
Flyby miss linearized time if B-vector were zero

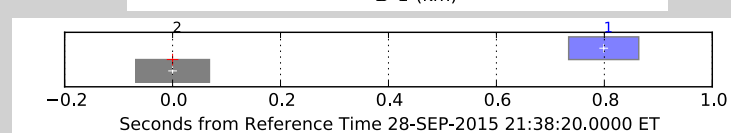
$$\mathbf{\Delta V} = -\mathbf{K}^{-1}\mathbf{\Delta B}$$

$$\mathbf{K} = \begin{bmatrix} \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_x} & \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_y} & \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_z} \\ \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_x} & \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_y} & \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_z} \\ \frac{\delta TF}{\delta V_x} & \frac{\delta TF}{\delta V_y} & \frac{\delta TF}{\delta V_z} \end{bmatrix}$$

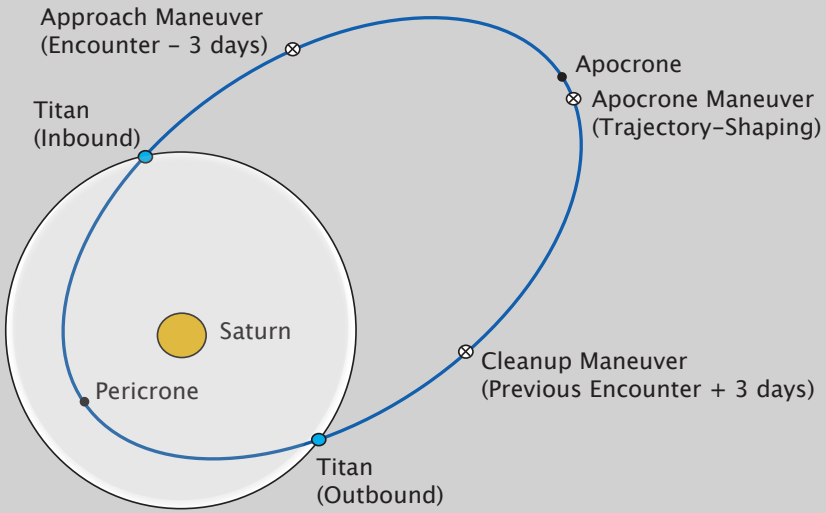
Example: Targeting T113







Navigation Strategy



Orbit Trim Maneuvers (OTMs)

$\Delta V \geq 0.25$ m/s → Main Engine Assembly (bipropellant)
$\Delta V < 0.25$ m/s → Reaction Control Subsystem (hydrazine)

3 OTMs per targeted flyby
B-plane target conditions
Cleanup is optimized with Apocrone maneuver

Exploit **Titan gravity assists**
Titan flyby at 1,000 km imparts 840 m/s to S/C
98% of total ΔV for the mission is provided by Titan

Key Strategy: propellant preservation is highly prioritized over maneuver cycle minimization

- Downstream ΔV preservation
- As close as possible to the reference trajectory

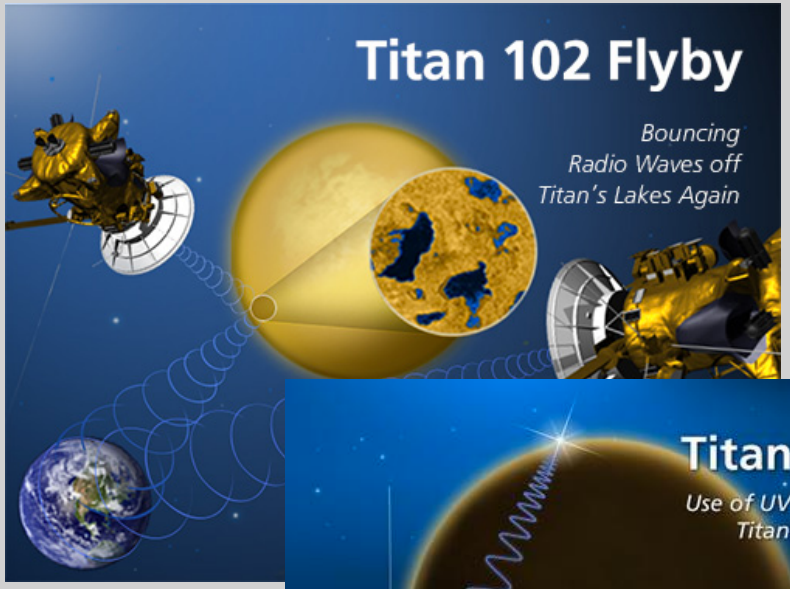
50 Planned Orbit Trim Maneuvers (OTMs 383-433) targeted to 17 satellite encounters:

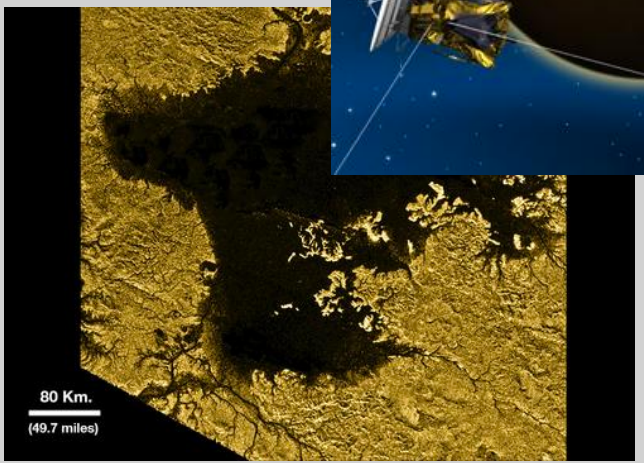
- 14 canceled OTMs: 1/3 maneuvers cancelled
- 8 maneuvers on MEA and 28 maneuvers on RCS
- Two target modifications to the B-plane spatial components (ΔV savings downstream)
- Three modification to the encounter time (increase ΔV to implementable size)

12 Titan, 3 Enceladus, 2 Dione Encounters

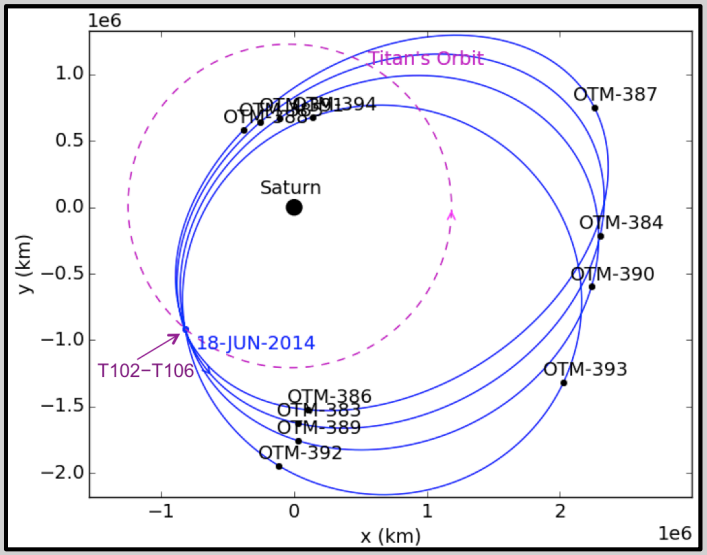
- Nine resonant transfers: 2:1, 3:1, 4:3 resonant ratios

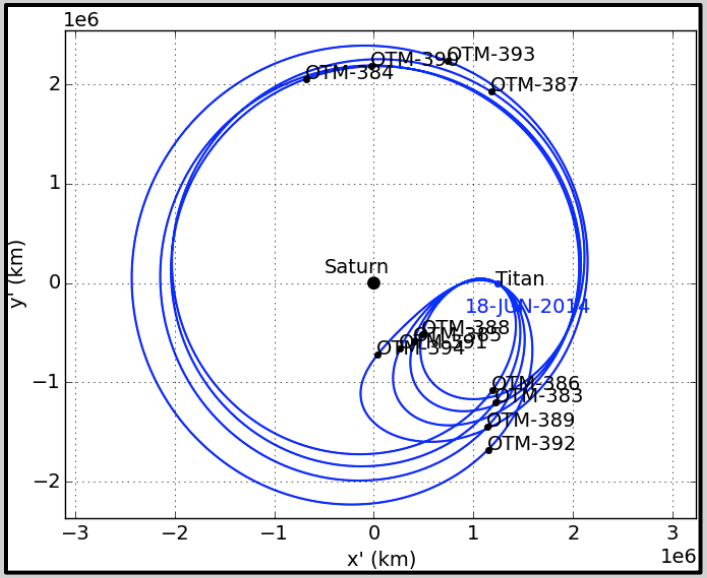
17 Titan Encounters





Titan-102 to Titan-106: 2:1 Resonant Transfers

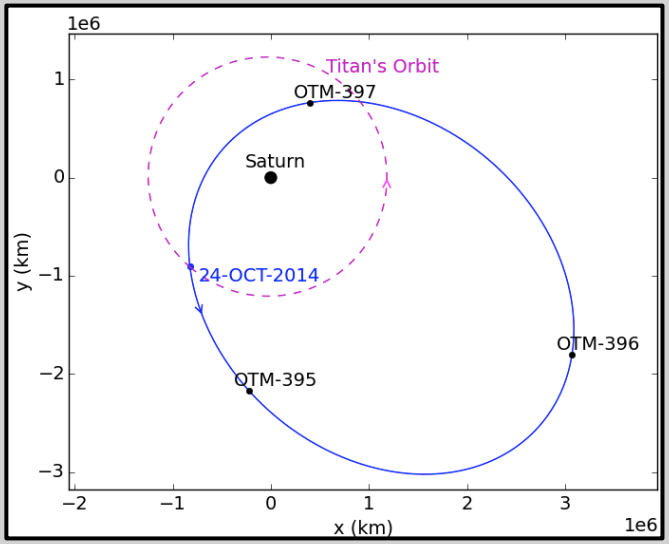


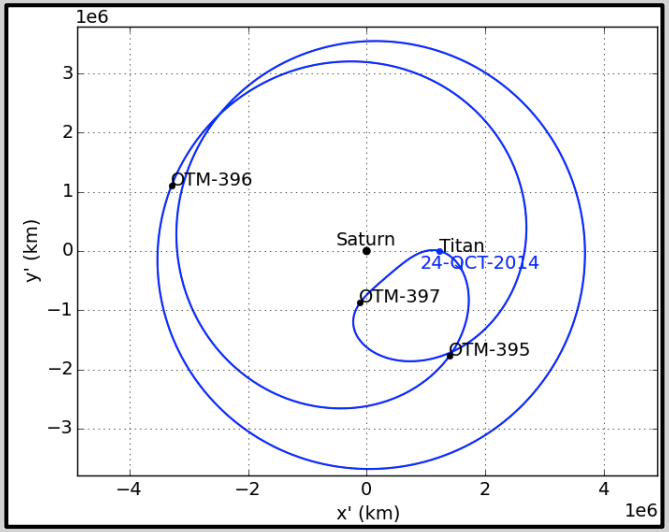


- Titan-to-Titan *n*:*m* resonant transfer → TOF is an integer multiple of Titan's period
  - *n* = number of Titan orbits around Saturn
  - *m* = number of Cassini revolutions around Saturn
- Flybys occur at approximately the same place in Titan's orbit
- Resonant transfers may be inclined

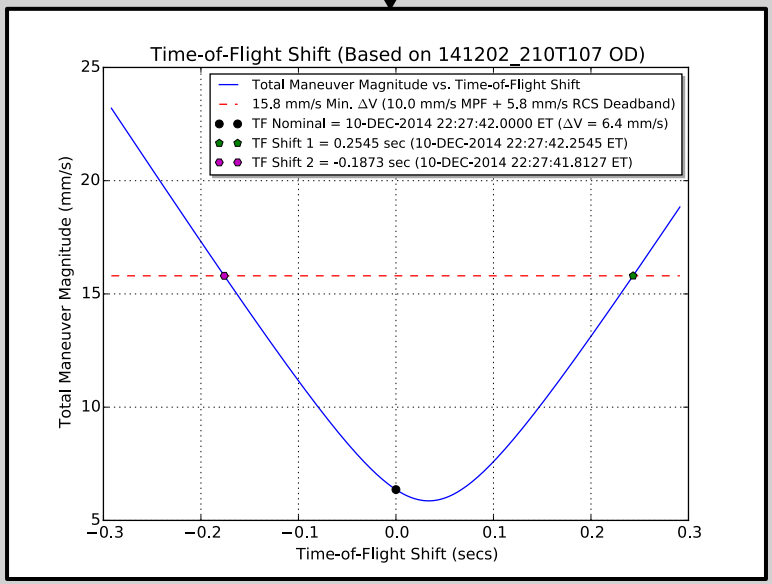
Titan-102	18-Jun-2014	Alt. 3,659 km
Titan-103	20-Jul-2014	Alt. 5,103 km
Titan-104	21-Aug-2014	Alt. 964 km
Titan-105	22-Sep-2014	Alt. 1,400 km
Titan-106	24-Oct-2014	Alt. 1,013 km

Titan-106 to Titan-107: 3:1 Resonant Transfer

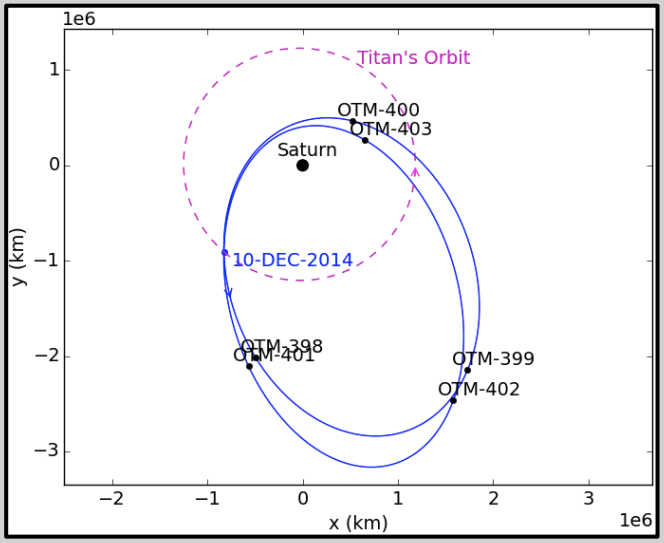




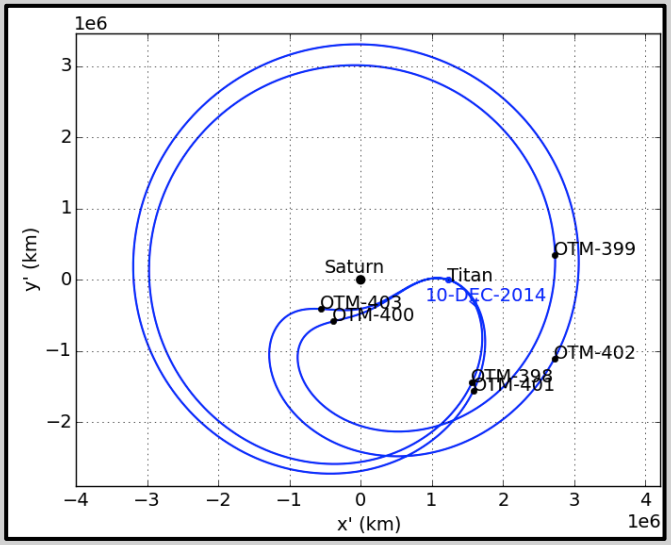
Maneuver	Epoch	ΔV
Titan-106	24-Oct-2014	Alt. 1,013 km
OTM-395	T106 + 2d	0.062 m/s
OTM-396	~ Apo	0.198 m/s
OTM-397	T107 – 3d	0.037 m/s
Titan-107	10-Dec-2014 **TOF Shift +0.4s**	Alt. 980 km



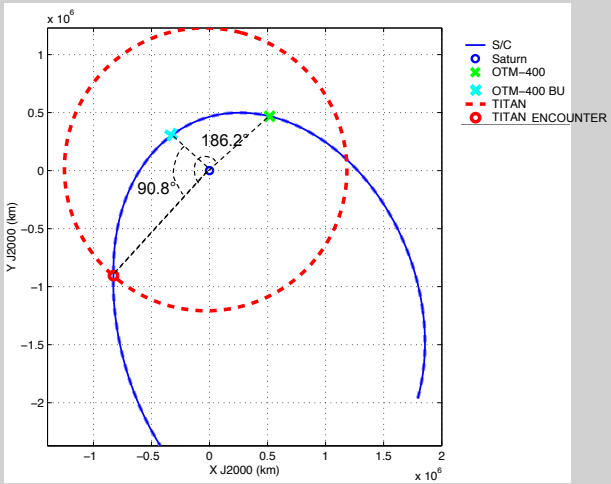
Titan-107 to Titan-109: 2:1 Resonant Transfer

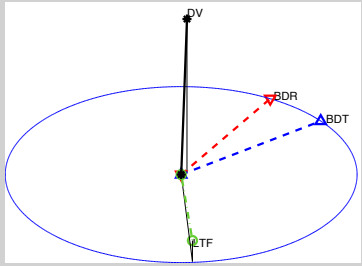


Maneuver	Epoch	ΔV
Titan-107	10-Dec-2014	Alt. 10,953 km
OTM-398	T107 + 3d	0.196 m/s
OTM-399	~ Apo	0.968 m/s
OTM-400BU	**T108 – 3d**	**0.056 m/s**
Titan-108	11-Jan-2015	Alt. 479 km

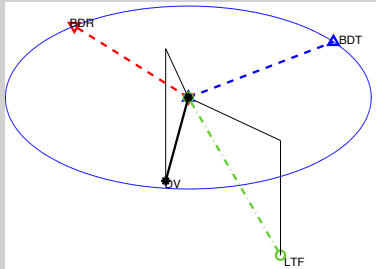


OTM-400 Geometry





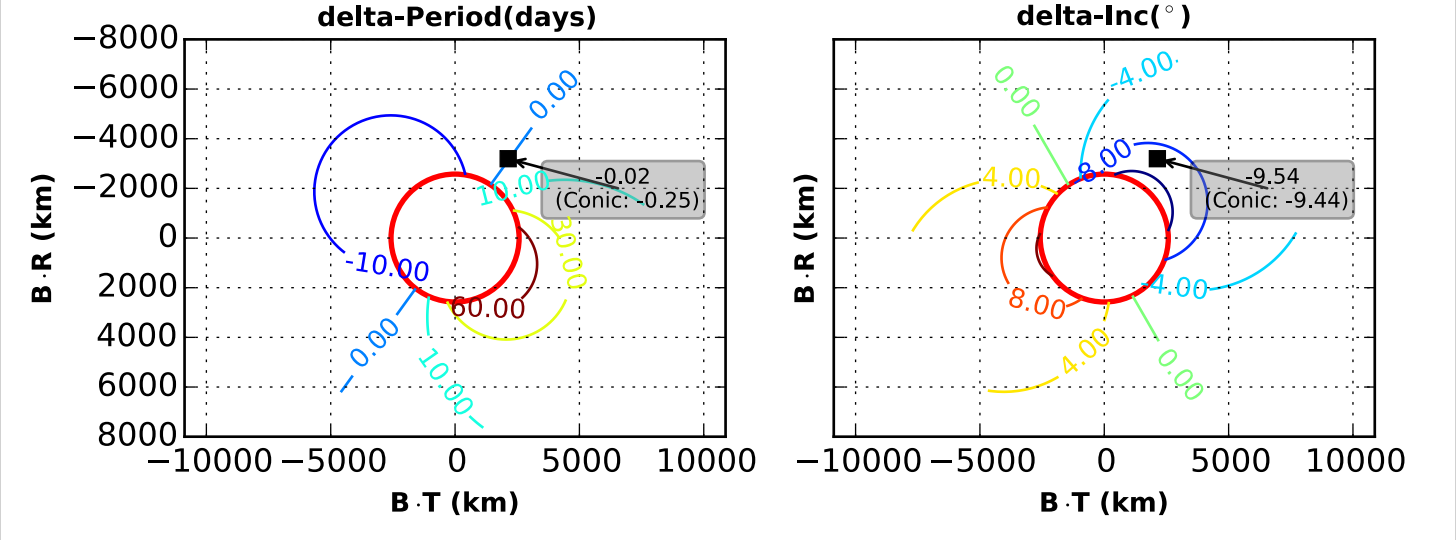
OTM-400: Central Angle 186.2°



OTM-400 BU: Central Angle 90.8°

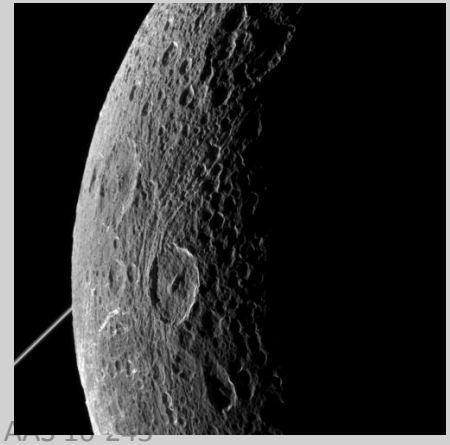
Titan-107 to Titan-109: 2:1 Resonant Transfer

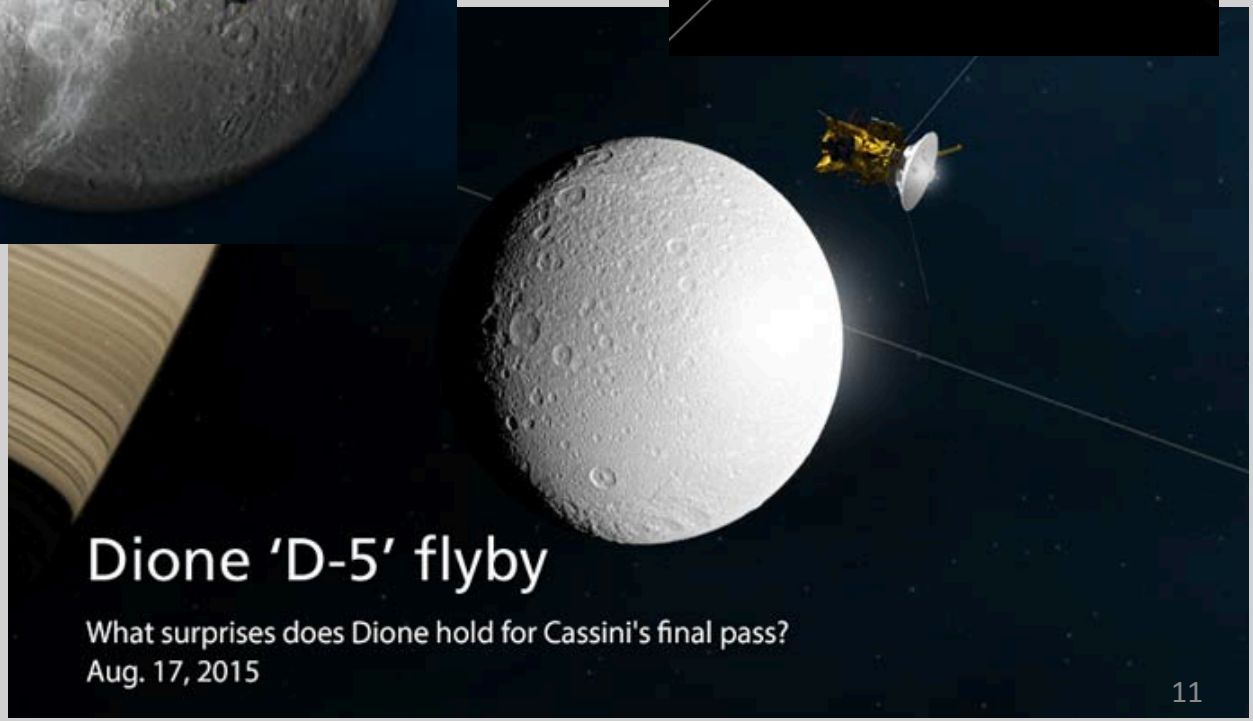
Maneuver	Epoch	ΔV
Titan-108	11-Jan-2015	Alt. 479 km
OTM-401	T108 + 3d	0.229 m/s
OTM-402	~ Apo	1.268 m/s
OTM-403	T109 – 3d	0.029 m/s
Titan-109	12-Feb-2015	Alt. 1,036 km



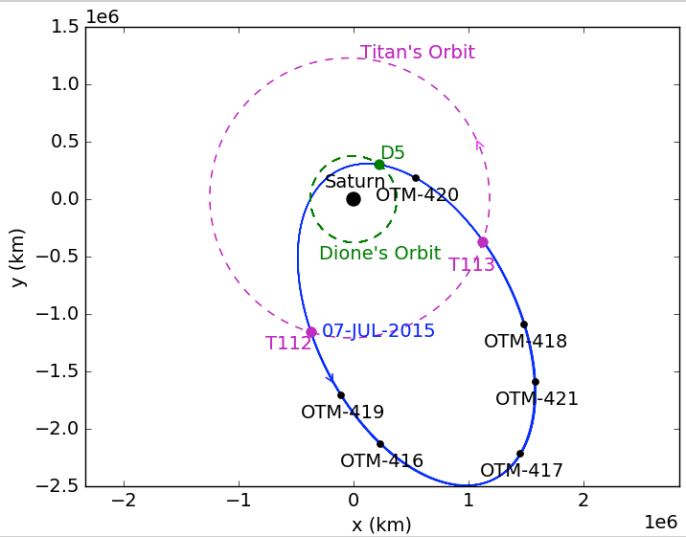
T108 Encounter: No period variation and 10 degrees inclination reduction

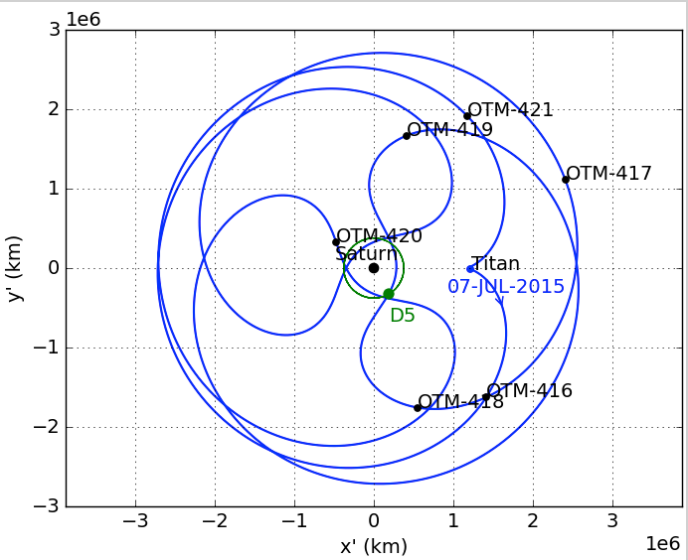
The Last Targeted Dione Encounters





The Last Targeted Dione Encounters



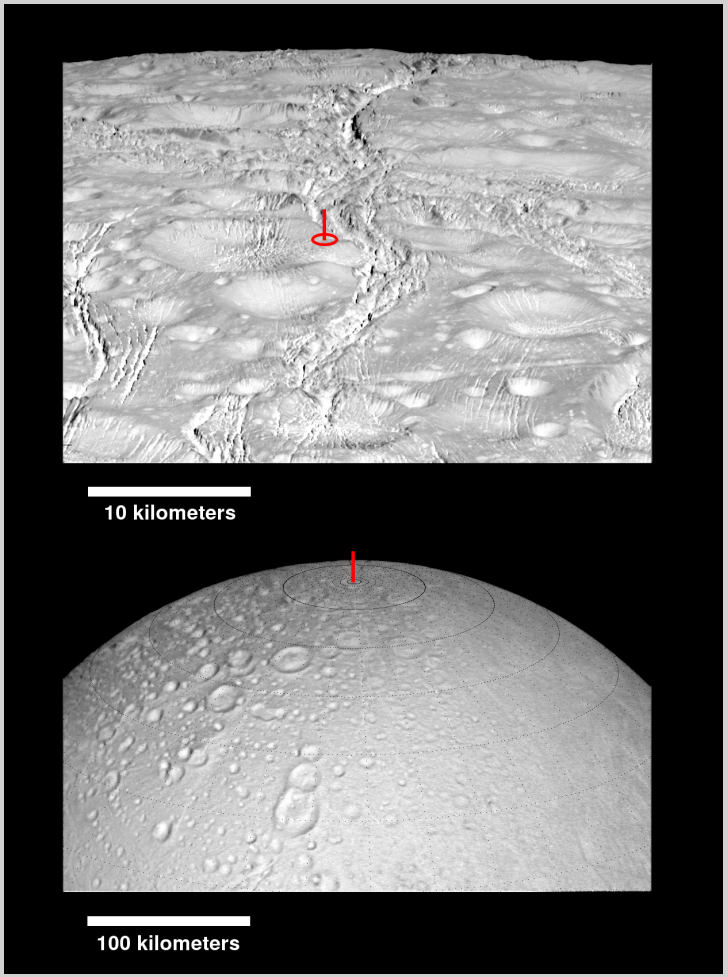


Maneuver	Epoch	ΔV
Titan-112	7-Jul-2015	Alt. 10,953 km
OTM-416	T113 + 2d	0.096 m/s
OTM-417	~ Apo	0.018 m/s
OTM-418	D5 – 3d	-- *canceled* --
Dione-5	17-Aug-2015	Alt. 479 km
OTM-419	D5 + 3d	0.058 m/s
OTM-420	~ Apo	-- *canceled* --
OTM-421	T113 – 3d	0.022 m/s
Titan-113	28-Sep-2015	Alt. 1,036 km

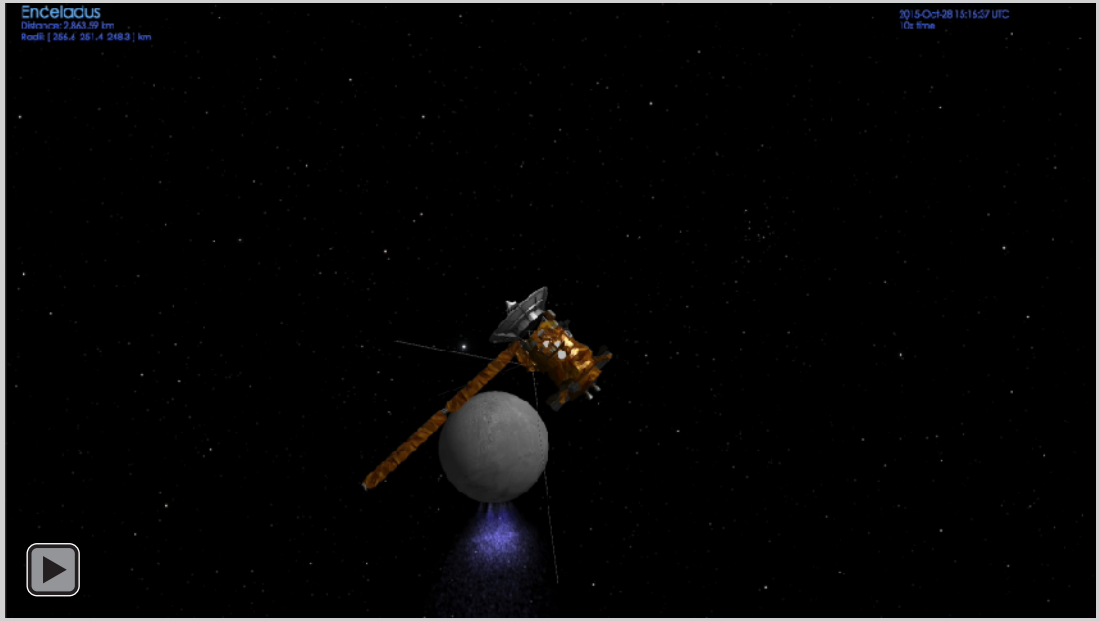
The Last Targeted Enceladus Encounters

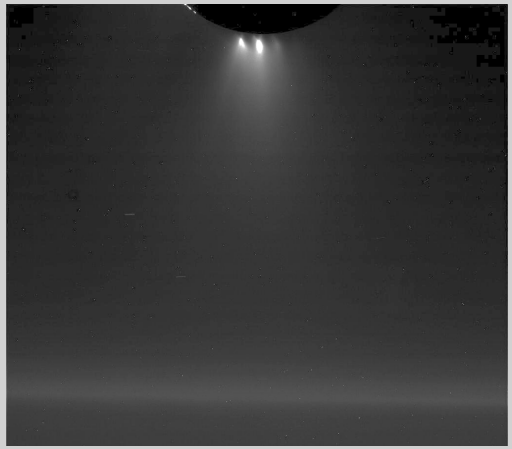
The Last Targeted Enceladus Encounters

E20 Flyby: North Pole

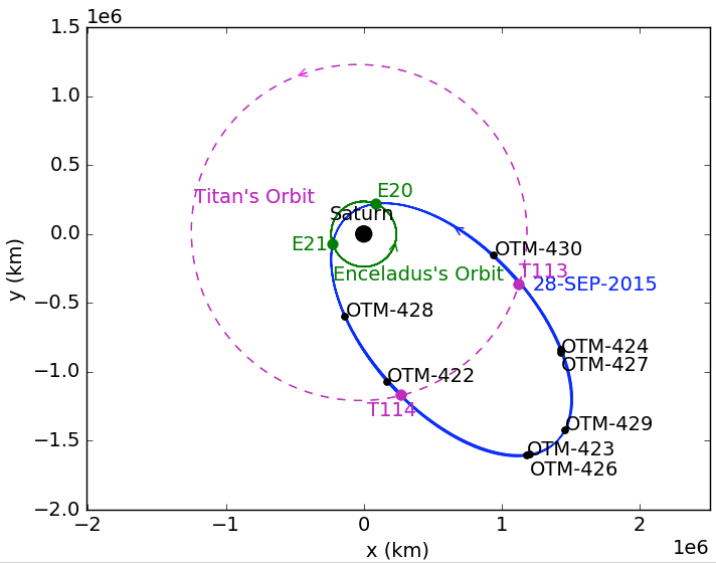


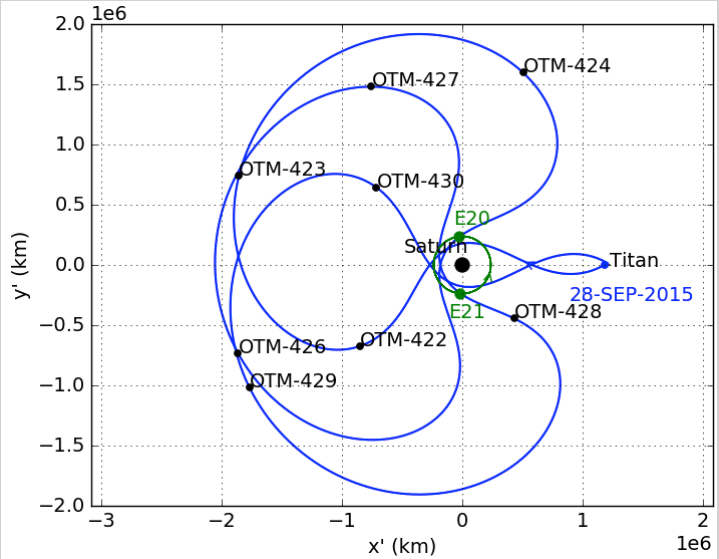
E21 Flyby: Deepest dive through plumes





The Last Targeted Enceladus Encounters



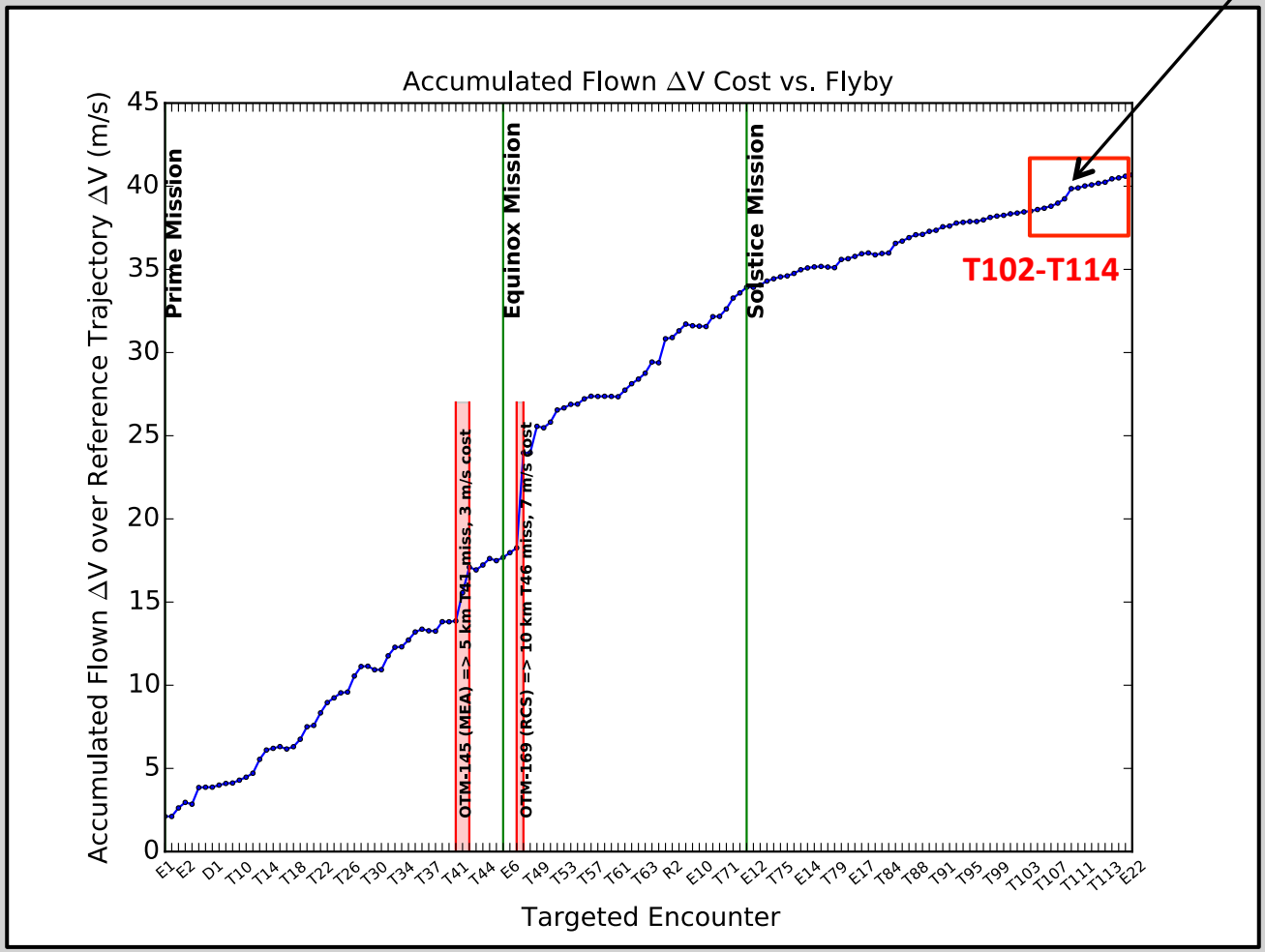


Maneuver	Epoch	ΔV
Titan-113	28-Sep-2015	Alt. 1,036 km
OTM-422	T113 + 3d	0.252 m/s
OTM-423	~ Apo	2.626 m/s
OTM-424	E20 – 3d	0.034 m/s
Enceladus-20	14-Oct-2015	Alt. 1,846 km
OTM-426	~ Apo	0.070 m/s
OTM-427	E21 – 3d	-- *canceled* --
Enceladus-21	28-Oct-2015	Alt. 50 km
OTM-428	E21 + 3d	-- *canceled* --
OTM-429	~ Apo	0.111 m/s
OTM-430	T114 – 3d	-- *canceled* --
Titan-114	13-Nov-2015	Alt. 11,920 km

Accumulated Flown DV Cost

Mission	Flyby Span	Number of Flybys	Navigation ΔV Cost	
			Mean (m/s)	Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta – E4	54	0.325	0.594
Equinox (9/2008 – 9/2010)	E5 – T72	36	0.447	0.978
Solstice (9/2010 – 12/2015)	T73 – E22	58	0.123	0.131

1 km miss at T109: 0.61 m/s immediate navigation cost (deterministic cost 0.006 m/s)

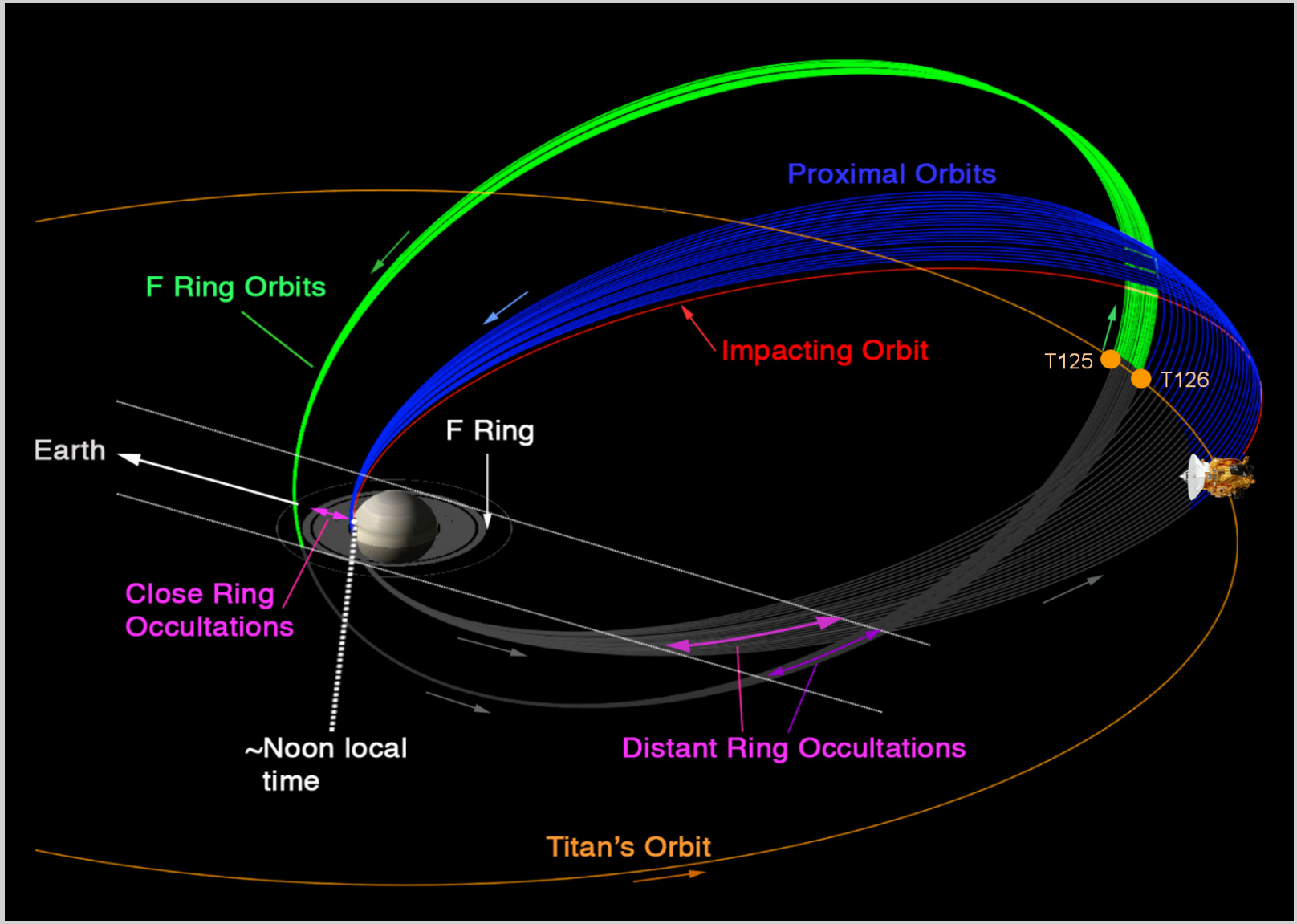


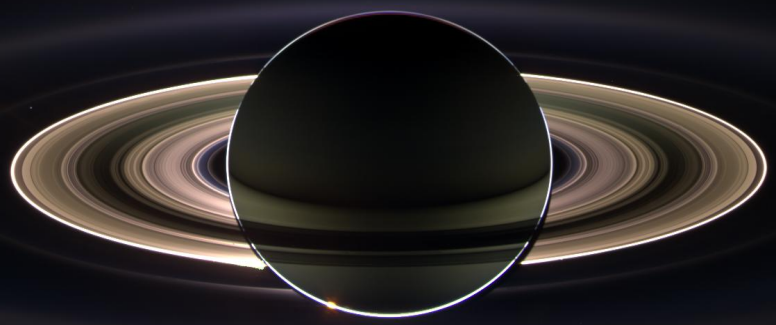
End-of-Mission in September 2017

- Preservation of propellant to achieve 2017 end-of-mission is highly prioritized
  - Save downstream costs to ensure hydrazine reserves for RCS
    - Small maneuvers
    - Spacecraft pointing
    - Momentum management
  - MEA Bi-propellant is dwindling
    - OTM-444 to target T118 has 7.4% chance of running out

DV Available (90%)	Jan. 2016	Sep. 2017
MEA	18 m/s	0 m/s
RCA	34 m/s	23 m/s

End-of-Mission in September 2017





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