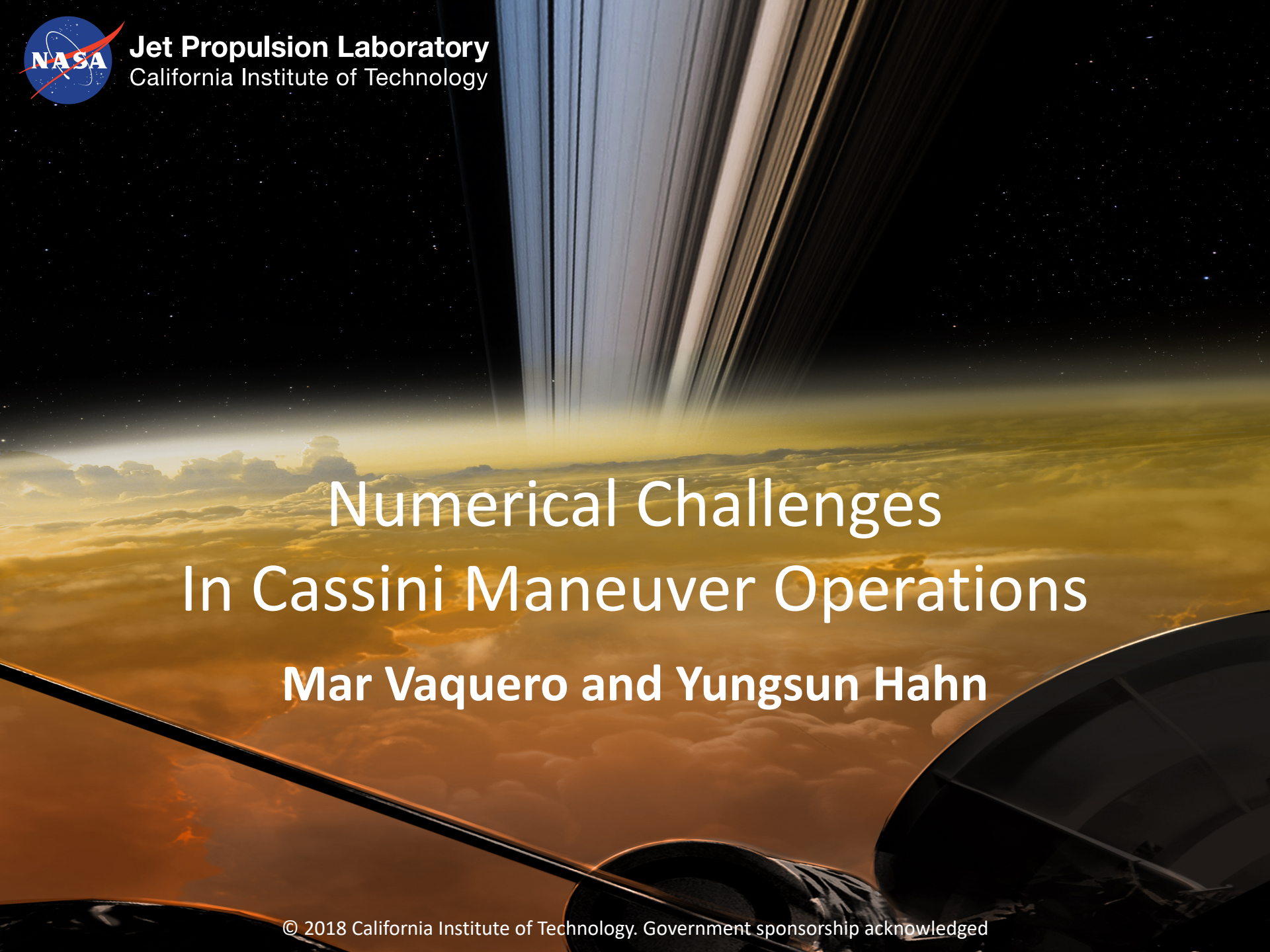
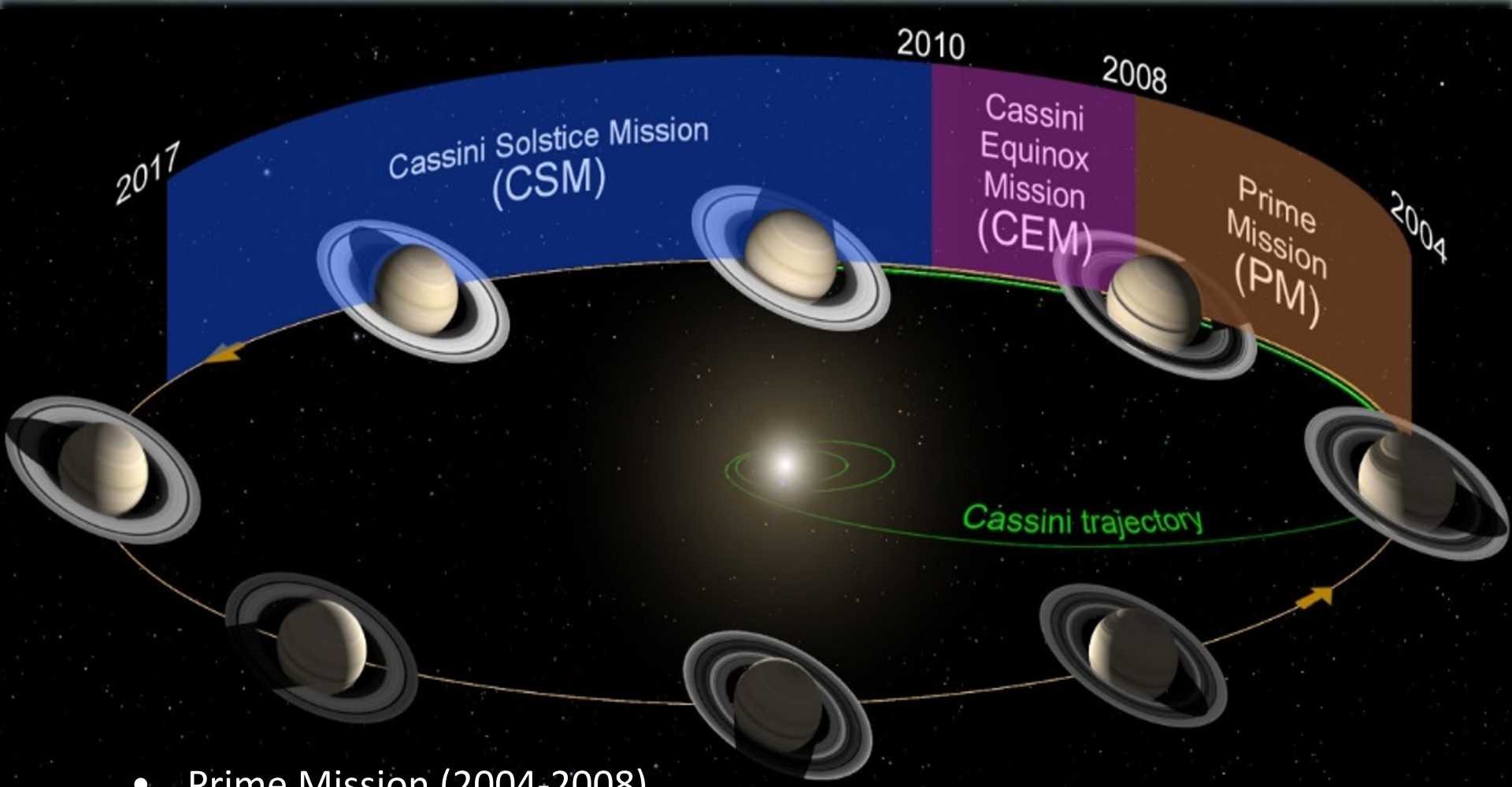


Jet Propulsion Laboratory
California Institute of Technology

Numerical Challenges In Cassini Maneuver Operations

Mar Vaquero and Yungsun Hahn

A Brief History of Cassini



- Prime Mission (2004-2008)
- Equinox Mission (2008-2010)
- Solstice Mission (2010-2017)

Nov '02 | Aug '09 | May '17 | May '25 | Abr '32

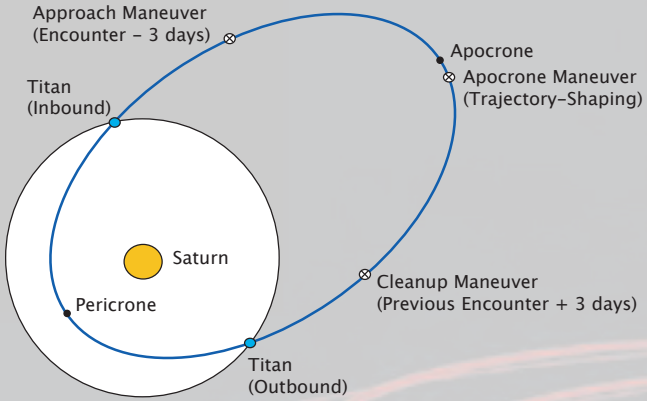
Cassini Grand Finale

Maneuver Challenges during the Tour

3 Orbit Trim Maneuvers per targeted flyby

$\Delta V \geq 0.25$ m/s → Main Engine Assembly (bipropellant)

$\Delta V < 0.25$ m/s → Reaction Control Subsystem (hydrazine)



CLEAN-UP BURNS

- Large ΔV differences between pre-flyby and post-flyby solutions
- Wheel speeds issues

TARGETING BURNS

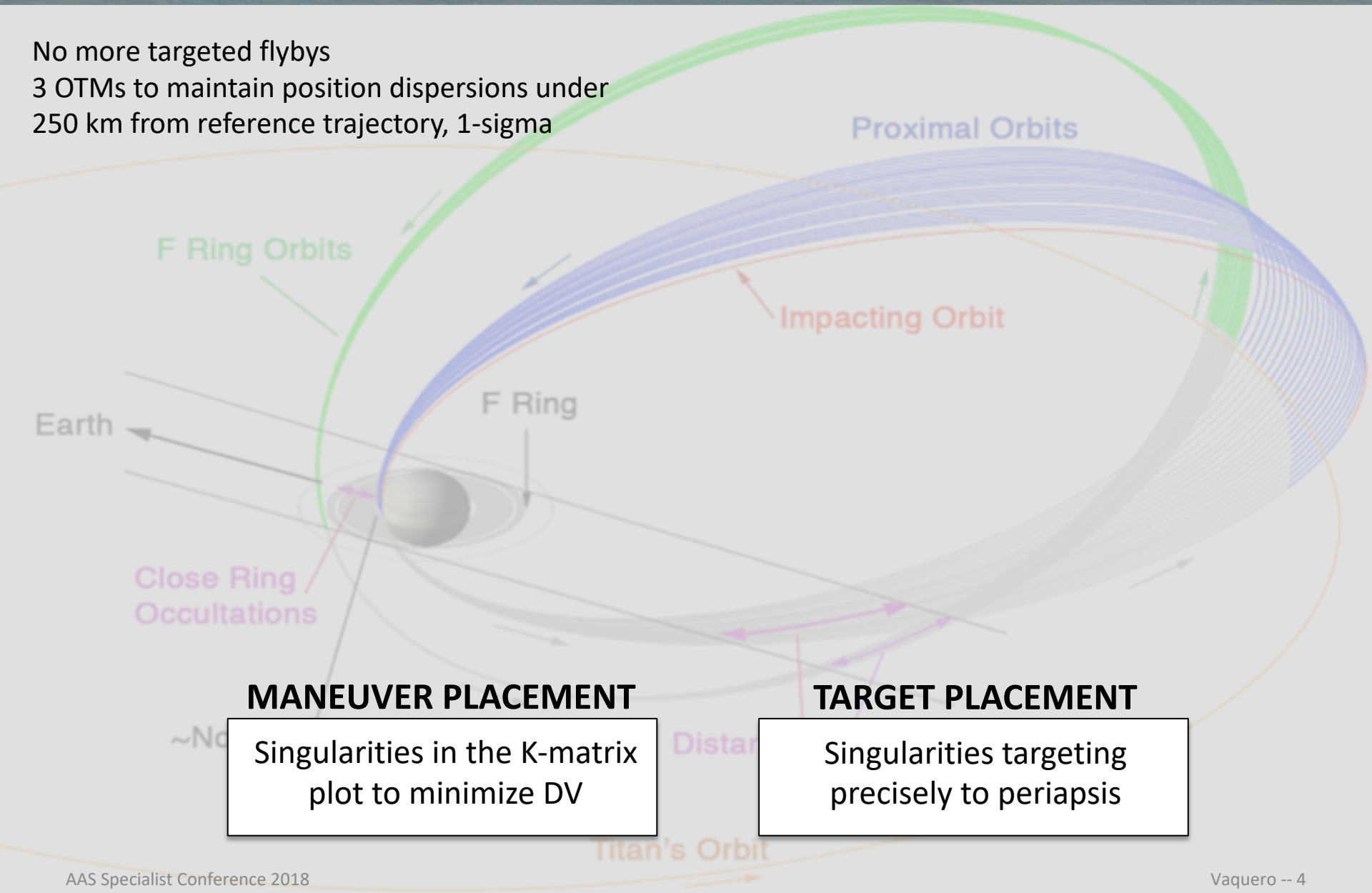
- Orbital dynamics instabilities
- Integration tolerance anomalies

APPROACH BURNS

- Minimum implementable size
- Near-pi transfer singularity

Challenges during the Grand Finale

No more targeted flybys
3 OTMs to maintain position dispersions under 250 km from reference trajectory, 1-sigma



MANEUVER PLACEMENT

Singularities in the K-matrix plot to minimize DV

TARGET PLACEMENT

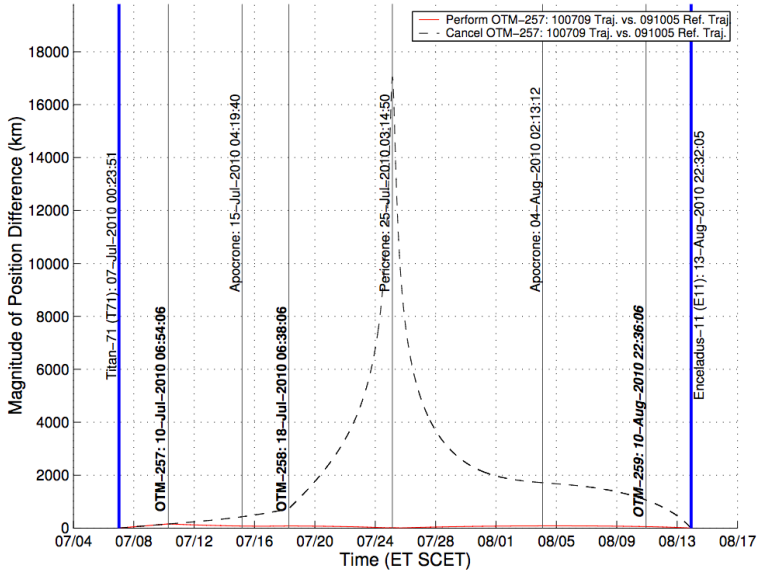
Singularities targeting precisely to periapsis

Clean-Up Burns

OTM-257 Targeting to Enceladus-11

Change in Asymptote

- Pre-flyby solution: RCS size (0.21 m/s)
- Titan flyby error within 1-sigma
- Post-flyby solution: MEA size (0.84 m/s)
- Large asymptote change
- High burn cancellation penalty > 8 m/s
- Large trajectory deviations > 16000 km @ pericrone



T71 to E11 = 37.9 days, 1.5 revs., 3 mvrs. (2 deterministic, 1 statistical)

OTM-338 Targeting to Titan-89

Sensitivities in Optimization Chain Process

- Drastic changes in ΔV direction (raan & dec)
- Pre-flyby solution: MEA size (0.3 m/s)
- Post-flyby solution: RCS size (0.028 m/s)
- Large variations in direction (>30 deg)
- Multiple local minima in solution space
- Numerical sensitivity caused by the presence of multiple solutions adding up to the same total
- Different solutions yielded different wheel speed profiles → problem for AACS Team
- Solution: select a feasible design and constrain direction in subsequent optimizations to force the optimizer to find the same solution

Orbit location	Titan-88 + 4 days
Right Ascension	227.95 deg
Declination	-47.66 deg
Roll Turn	153.23 deg
Yaw Turn	-142.38 deg

Targeting Maneuvers

OTM-159 from Prime to Extended Mission

Orbital Dynamics Instabilities

- Observed during burns located near periapsis, resulting in no viable prime or backup solutions
- Nominal burn: 12 m/s
- Backup burn: 32 m/s + 97 m/s penalty downstream
- Alternative: delay backup by one week
  - Redesign trajectory: remove 1 Enceladus flyby and alter 7 Titan flybys
  - New backup burn: from 32 m/s to 19 m/s (8 m/s of downstream penalty)
- **Solution:** Early uplink with multiple windows

OTM-450 Targeting to Titan-120

Integration Tolerance Anomaly

- Pure numerical propagation issues
- State tolerance of 10^{-13} vs 10^{-14} resulted in a difference of 4.5 km in the B-Plane and 0.56 sec in flyby encounter time
- Anomaly observed when running one software version only
- **Solution:** tighten the propagator tolerance

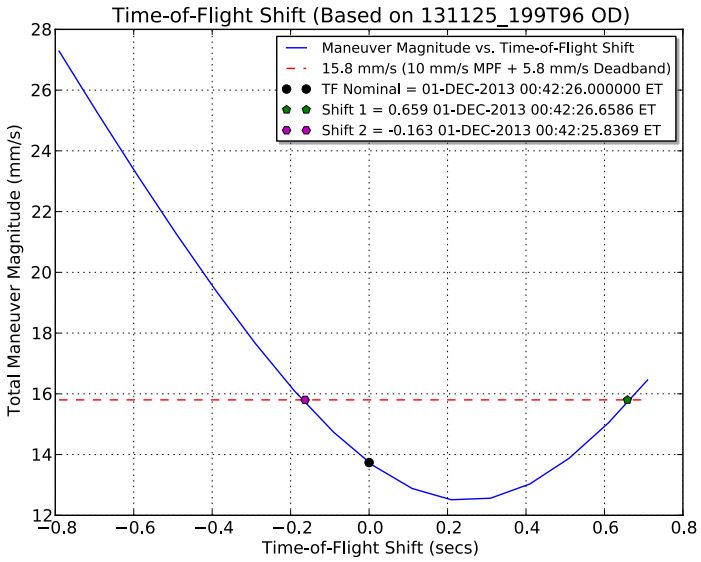
State Tolerance	10^{-13}	10^{-14}
B·R	3114.028 km	3114.59 km
B·R	-2308.88	-2304.33 km
Time to Periapsis	-7.56 sec	7.00 sec

Approach Maneuvers

OTM-362 3:1 Resonant Transfer

Minimum Implementable Burn Size

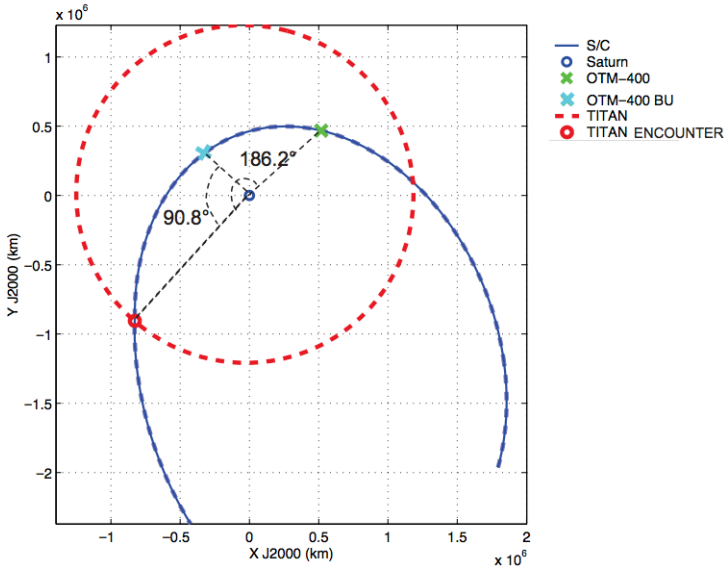
- Minimum implementable ΔV = 14 mm/s
- Nominal OTM-362 design = 7.7 mm/s
- High cancelation cost (0.75 m/s)
- **Solution:** add a time-of-flight bias to increase the ΔV magnitude
- Titan-96 encountered was modified by 0.75 sec to increase size of OTM-362 from 7.7 mm/s to 14 mm/s



OTM-400 Targeting to Titan-108

Near-Pi Transfer Singularity

- Central angle (between burn and encounter location) is close to the 180 deg singularity point
- B-plane target gradients become coplanar and the inverse of targeting matrix becomes singular
- Maneuver solution extremely unstable
- Central angle for backup burn 1 day later = 90deg
- **Solution:** execute OTM-400 on backup pass

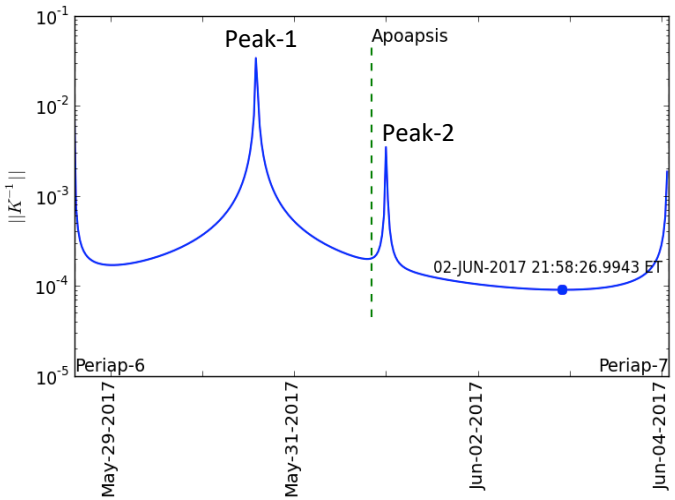


Proximal Maneuvers

Minimizing ΔV using K-Matrix

Double Peak Singularity

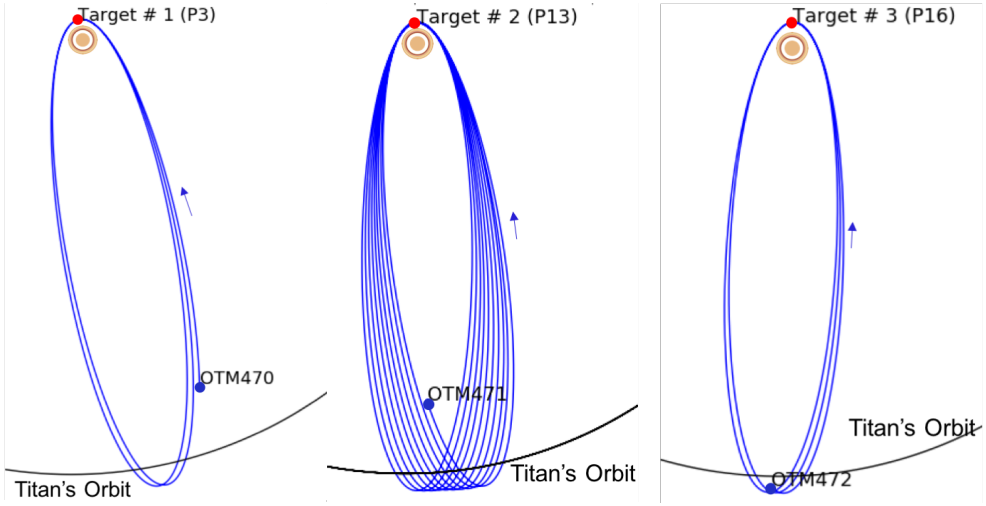
- $\Delta V = K^{-1}\Delta\bar{X}_f$ (K is 3x3 block of STM)
- Two peaks appear on ΔV curve
- Not a numerical artifact
- Origin of peak-1 is still undetermined
- Peak-1 only appears in multi-rev targeting
- Peak-2 caused by the 180 deg orbital transfer singularity in the Lambert problem
- Peak-2 accentuated by Saturn J2 effects
- **Solution:** move burn away from peaks



Targeting to Periapsis

High ΔV

- Trajectory dispersions are largest by far at periapsis caused by timing errors
- Intuitively, targets placed at periapsis to control deviations from reference trajectory
- Singularity in the transfer problem results in prohibitively high ΔV
- **Solution:** move target from periapsis by 2 hrs



Summary

Most complex trajectory design ever flown: 492 maneuver designs and 160 flybys
Required continuous re-evaluation of maneuver decision, redesign and cancellation processes

PROCESSES

Astrodynamical singularities encountered during operations:

- singularities in the transfer problem
- numerical instabilities in state propagations through flybys
- maneuver algorithm convergence issues
- orbital element targeting difficulties

CHALLENGES

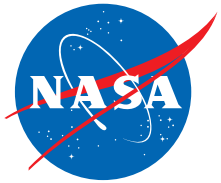
- Moving burns to less-than-optimal locations
- Delaying burns to backup pass to save propellant
- Increasing burn size to implementable range

SOLUTIONS

Saturn atmospheric entry achieved

Successful navigation strategy and OTM executions

Mar.Vaquero@jpl.nasa.gov



Jet Propulsion Laboratory
California Institute of Technology