Partner

TETHERED ARTIFICIAL GRAVITY ASSISTS FOR CAPTURE ABOUT BINARY ASTEROIDS IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM

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OVERVIEW

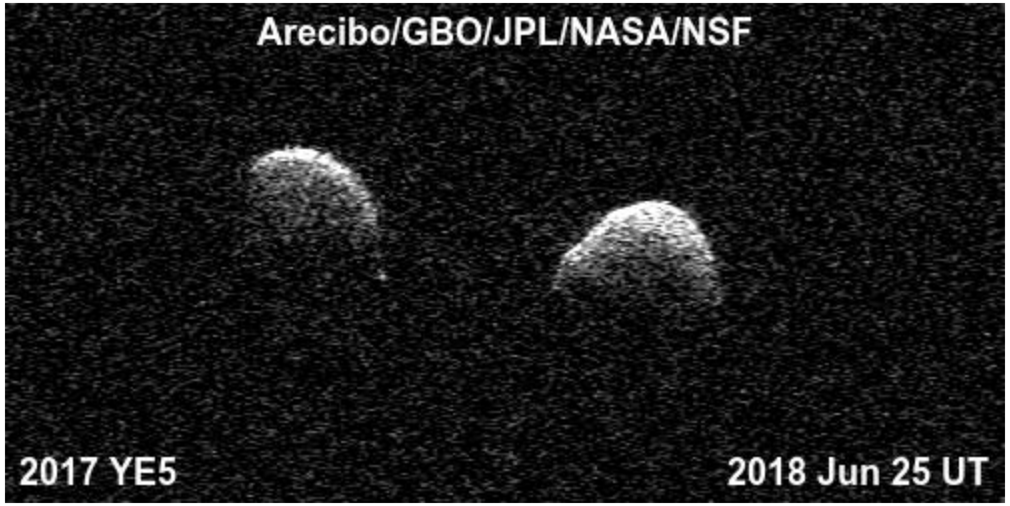

Credit: NASA/Johns Hopkins APL [1]

1. Introduction
2. Method
3. Simulation Scenarios
4. Results & Discussion
5. Conclusion & Future Work

INTRODUCTION

Tethered artificial gravity assist: a proposed alternative to traditional methods of propulsion that changes the orbital path of a spacecraft using a tether

Objective: Develop an approach to optimize tethered artificial gravity assist maneuvers in binary asteroid systems using the circular restricted three-body problem (CR3BP)



Credit: Arecibo/GBO/NSF/NASA/JPL-Caltech [2]

PROBLEM FORMULATION

Ratio of mass between secondary asteroid and total system [3]:

$$\mu = \frac{m_2}{m_1 + m_2}$$

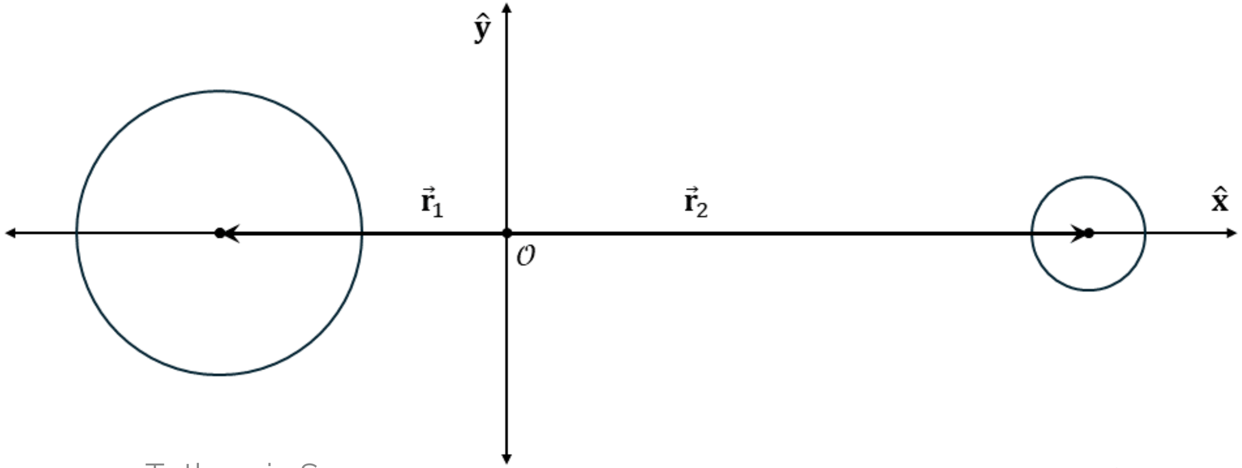
Normalized position of asteroids in synodic frame [3]:

$$\vec{r}_1 = \begin{bmatrix} -\mu \\ 0 \end{bmatrix}, \qquad \vec{r}_2 = \begin{bmatrix} 1-\mu \\ 0 \end{bmatrix}$$

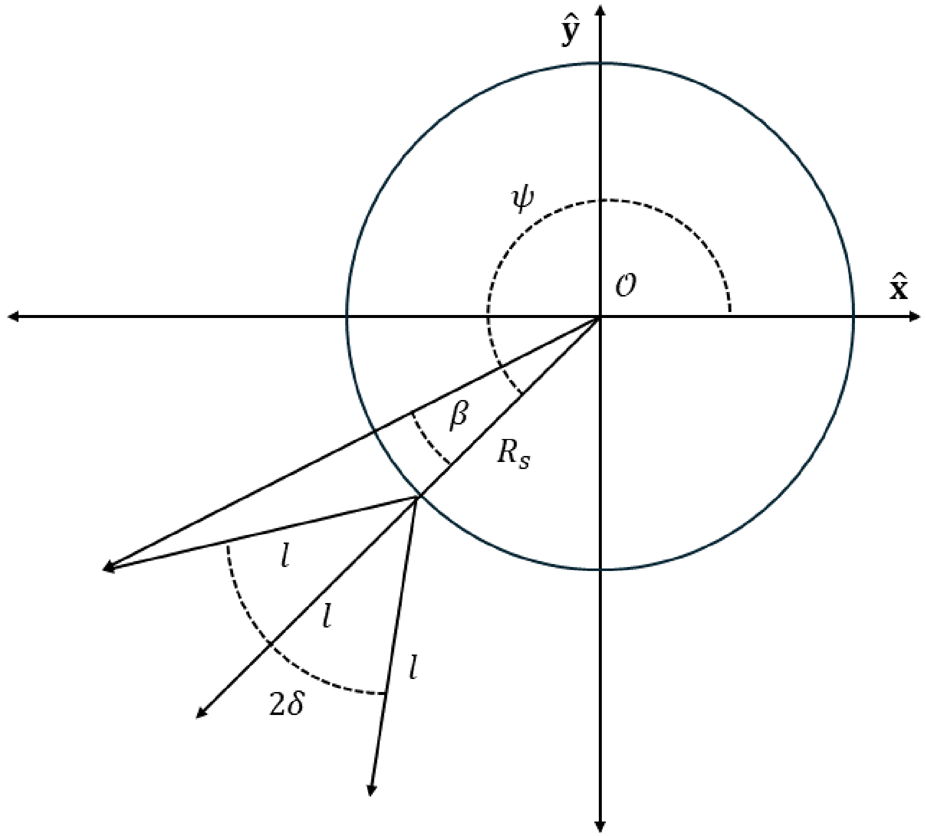
Normalized radii of asteroids:

$$R_p = \frac{R_1(1-\mu)}{a_s}, \qquad R_s = \frac{R_2(1-\mu)}{a_s}$$

Additional Parameters:
m_1 = real mass of primary
m_2 = real mass of secondary
R_1 = real radius of primary
R_2 = real radius of secondary
a_s = real semi-major axis of secondary



TETHER DYNAMICS



Tether Attachment [4]:

$$\vec{\mathbf{r}}_i = \begin{bmatrix} r_{x_i} \\ r_{y_i} \end{bmatrix} = \begin{bmatrix} l\cos(\psi+\delta) + R_s\cos\psi + (1-\mu) \\ l\sin(\psi+\delta) + R_s\sin\psi \end{bmatrix}$$

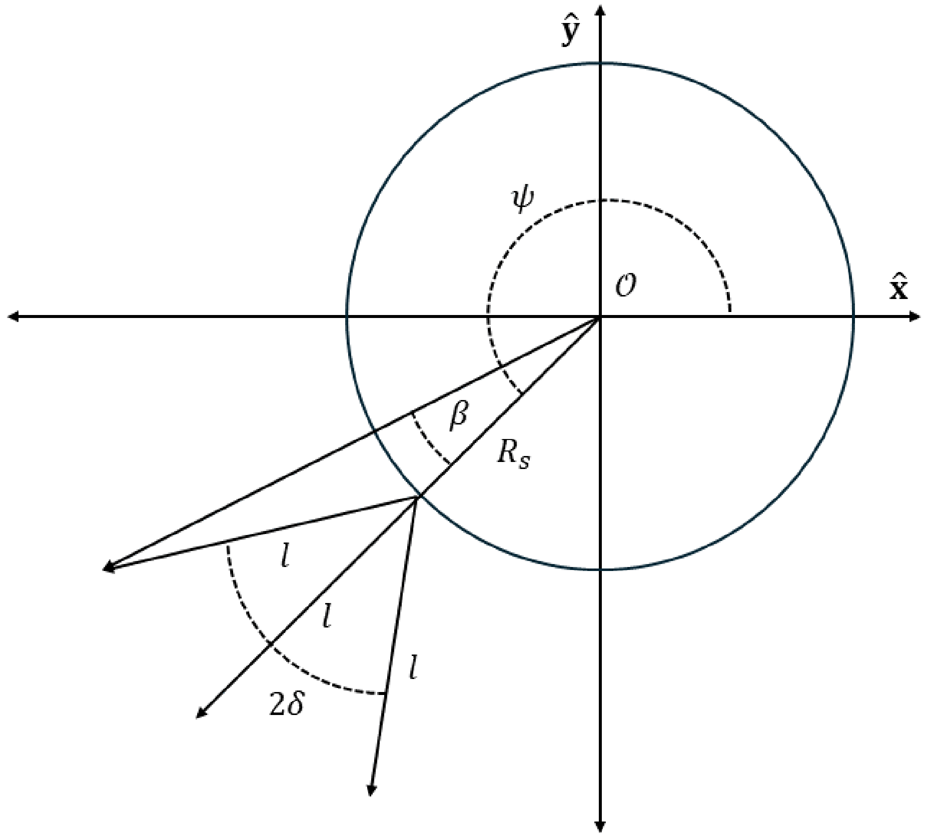
$$\vec{v}_i = \begin{bmatrix} v_{x_i} \\ v_{y_i} \end{bmatrix} = \begin{bmatrix} v_\infty\sin(\psi+\beta) \\ -v_\infty\cos(\psi+\beta) \end{bmatrix}$$

Tether Detachment [4]:

$$\vec{\mathbf{r}}_i = \begin{bmatrix} r_{x_i} \\ r_{y_i} \end{bmatrix} = \begin{bmatrix} l\cos(\psi-\delta) + R_s\cos\psi + (1-\mu) \\ l\sin(\psi-\delta) + R_s\sin\psi \end{bmatrix}$$

$$\vec{v}_i = \begin{bmatrix} v_{x_i} \\ v_{y_i} \end{bmatrix} = \begin{bmatrix} v_\infty\sin(\psi-\beta) \\ -v_\infty\cos(\psi-\beta) \end{bmatrix}$$

CR3BP DYNAMICS



Jacobi Constant: The only conserved value in CR3BP dynamics

Jacobi Constant [3]:

$$C_j = (1-\mu)r_p^2 + \mu r_s^2 + \frac{2(1-\mu)}{r_p} + \frac{\mu}{r_s} - v_\infty^2$$

Distance between spacecraft and each asteroid [3]:

$$r_p^2 = (r_x + \mu)^2 + r_y^2$$
$$r_p^2 = (r_x - 1 + \mu)^2 + r_y^2$$

OPTIMIZATION

<u>Genetic algorithm (GA)</u>: evolutionary algorithm for complex optimization problems with high modality

- Select a planar periodic capture orbit as a desired final orbit to insert the spacecraft into (described by $\vec{\mathbf{r}}_d$ and $\vec{\mathbf{v}}_d$)
- Design variables: ψ, δ, l, $\vec{\mathbf{r}}_d$ and $\vec{\mathbf{v}}_d$

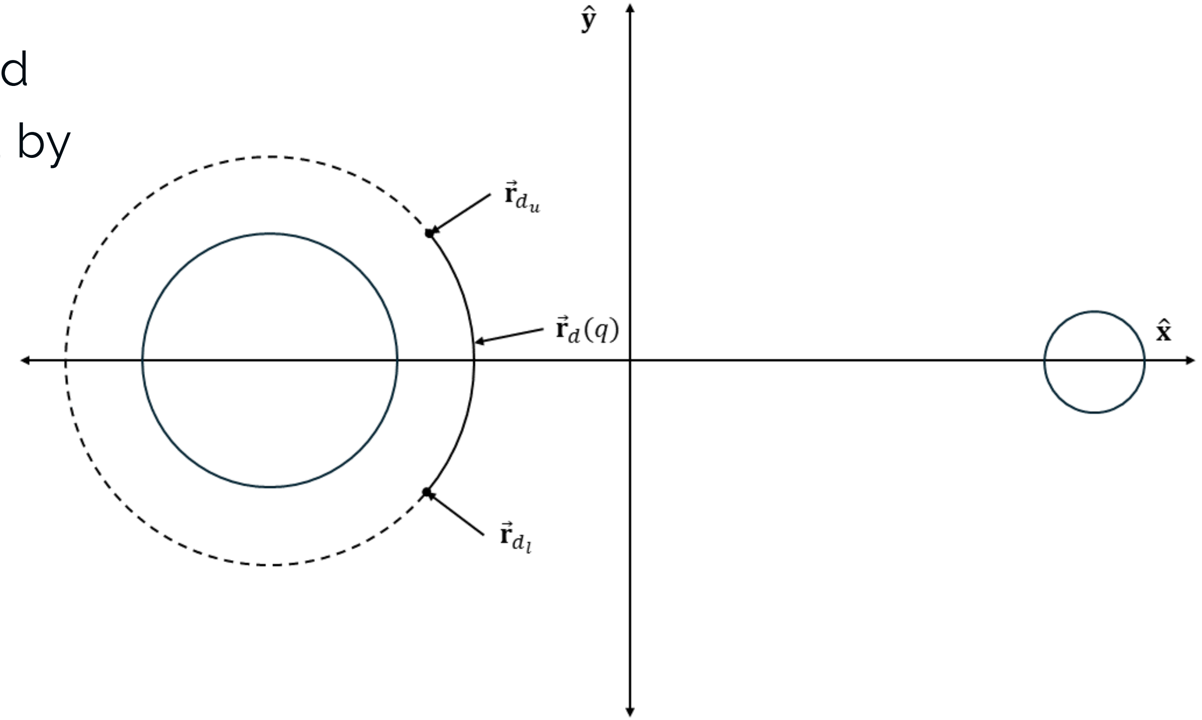
Objective Function:

$$J = -\omega_1 \left| C_{j_d} - C_{j_i} \right| + \omega_2 \left\| \vec{\mathbf{r}}_d - \vec{\mathbf{r}}_f \right\| + \omega_3 \left\| \vec{\mathbf{v}}_d - \vec{\mathbf{v}}_f \right\|$$

Constraints:

$$C_{j_i} > 0$$

$$\left\| \vec{r}_{i_{traj}} - \vec{r}_2 \right\| - R_p > 0$$



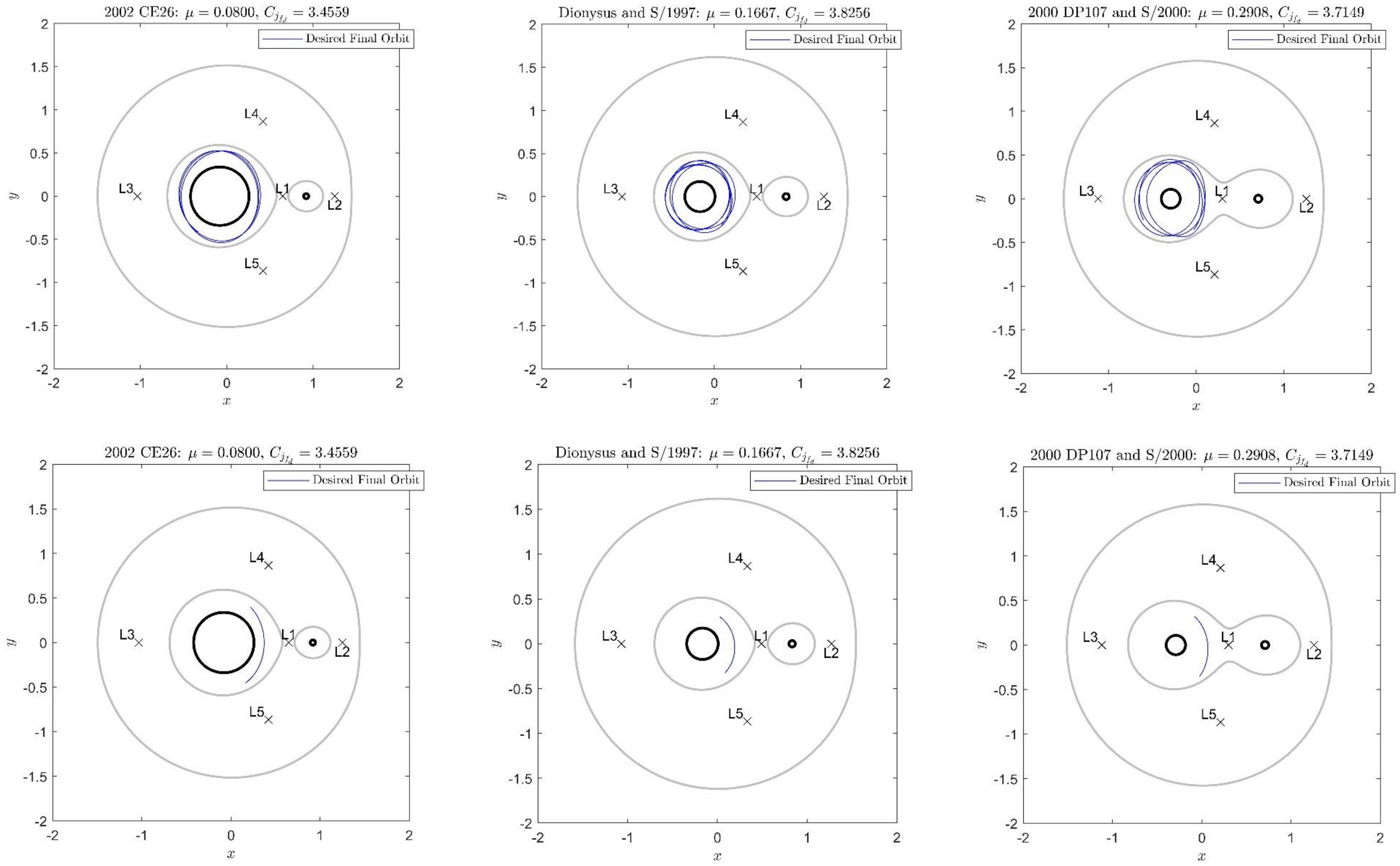
SIMULATION PARAMETERS

Criteria for selecting systems:

1. Enough data known to accurately simulate systems
2. Low orbital eccentricity observed in secondary
3. Categorize systems into different mass ratio ranges (i.e., small μ, medium μ, and large μ)
4. Largest distance between surface of primary to L_1 stability point

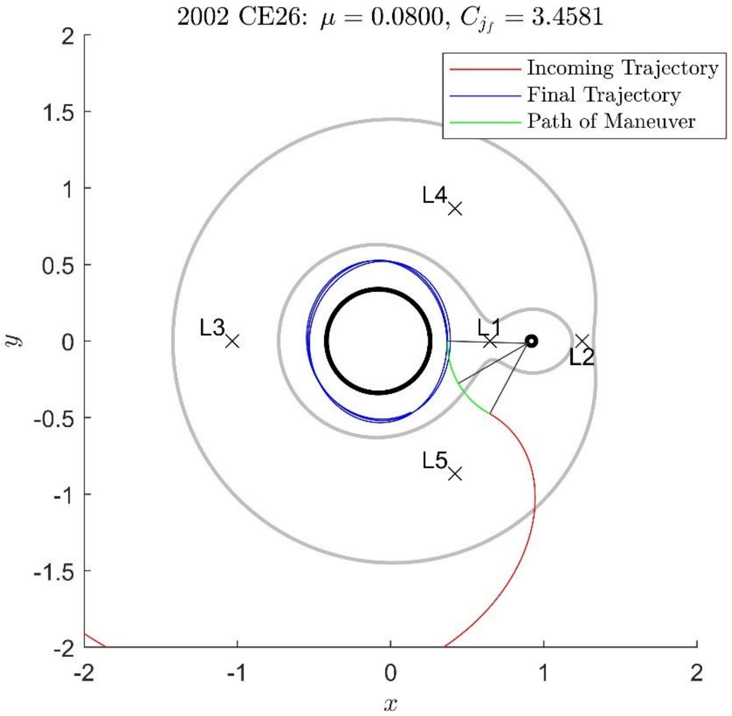
Observed Characteristics [5-9]			
Parameter	2002 CE26	Dionysus & S/1997	2000 DP107 & S/2000
μ	0.0800	0.1667	0.2908
m_T	1.95×10^{13} kg	2.48×10^{12} kg	4.6×10^{11} kg
d_P	3.46 km	1.43 km	0.8 km
e_s	0.00	0.07	0.01
a_s	4.7 km	3.4 km	2.62 km
d_s	0.3 km	0.29 km	0.3 km

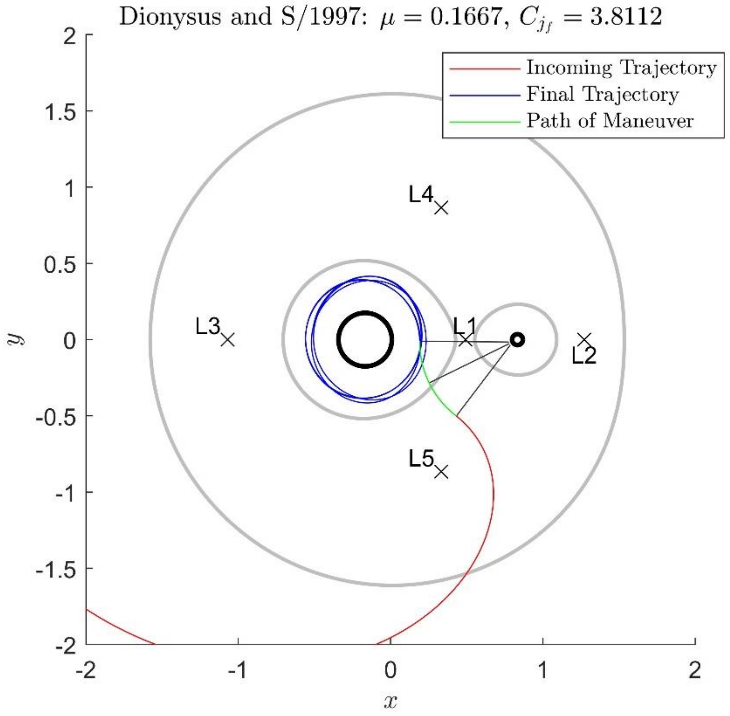
SIMULATION SCENARIOS

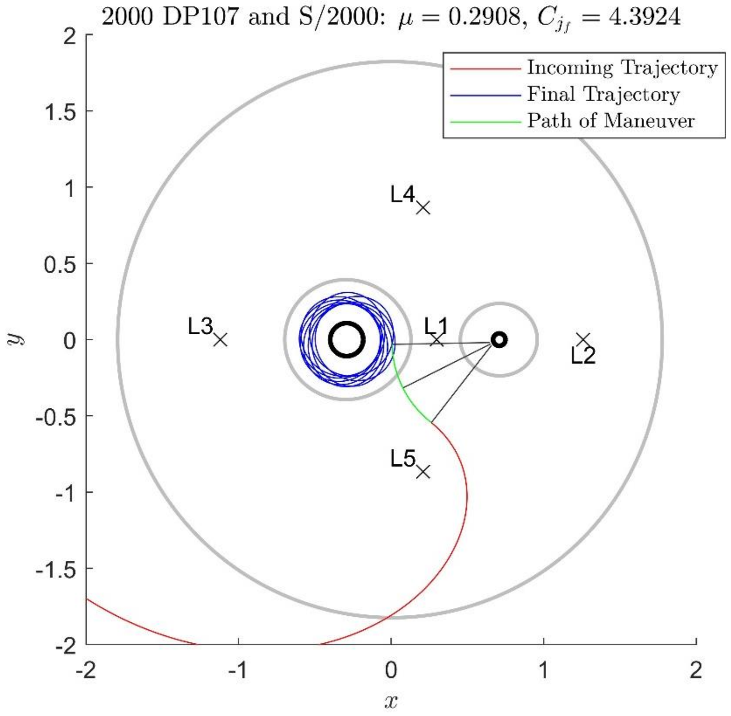


RESULTS

Optimized Tethered Maneuvers			
Design Variables	2002 CE26	Dionysus & S/1997	2000 DP107 & S/2000
ψ	210.12°	206.11°	206.64°
δ	31.73°	26.62°	25.51°
l	2.67×10^3 m	2.49×10^3m	2.46×10^3m







RESULTS

- Minimal difference found between desired orbit and final orbit in 2002 CE26 and Dionysus & S/1997
- Larger distance between position vectors for 2000 DP107 & S/2000 caused a more circular final orbit shape

Difference between desired orbit and final orbit			
Parameter	2002 CE26	Dionysus & S/1997	2000 DP107 & S/2000
$\left\|\vec{\mathbf{r}}_f - \vec{\mathbf{r}}_d\right\|$	0.1275 m	5.9600 m	259.2802 m
$\left\|\vec{\mathbf{v}}_f - \vec{\mathbf{v}}_d\right\|$	0.0120 m/s	0.0370 m/s	0.0191 m/s
$\left\|C_{j_f} - C_{j_d}\right\|$	0.0022	0.0144	0.6775

DISCUSSION

- GA successfully optimized tethered artificial gravity assists in each binary system
- Initial trajectory orbited in same direction as final desired orbit and rotation of system
- Tether at detachment point was optimized to be nearly aligned with x-axis
- Positive trend observed between μ and ΔC_j

Change in Jacobi Constant

Parameter	2002 CE26	Dionysus and S/1997	2000 DP107 and S/2000
μ	0.0800	0.1667	0.2908
C_{j_i}	2.0166	1.6960	1.8426
C_{j_f}	3.4581	3.8112	4.3924
ΔC_j	1.4415	2.1152	2.5498

CONCLUSION & FUTURE WORK

- Successfully optimized tethered artificial gravity assist maneuvers in three binary asteroid systems using CR3BP dynamics
- Future work:
  - Incorporate external perturbations into model
  - Utilize varying-length tether in maneuver

Credit: NASA/Goddard/SwRI/ASU [10]

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THANK YOU

Any Questions?

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BACKUP SLIDES

TETHER DYNAMICS

Tether Attachment [4]:

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$$\vec{v}_i = \begin{bmatrix} v_{x_i} \\ v_{y_i} \end{bmatrix} = \begin{bmatrix} v_\infty\sin(\psi+\beta) \\ -v_\infty\cos(\psi+\beta) \end{bmatrix}$$

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$$\vec{v}_i = \begin{bmatrix} v_{x_i} \\ v_{y_i} \end{bmatrix} = \begin{bmatrix} v_\infty\sin(\psi-\beta) \\ -v_\infty\cos(\psi-\beta) \end{bmatrix}$$

Additional Parameters:

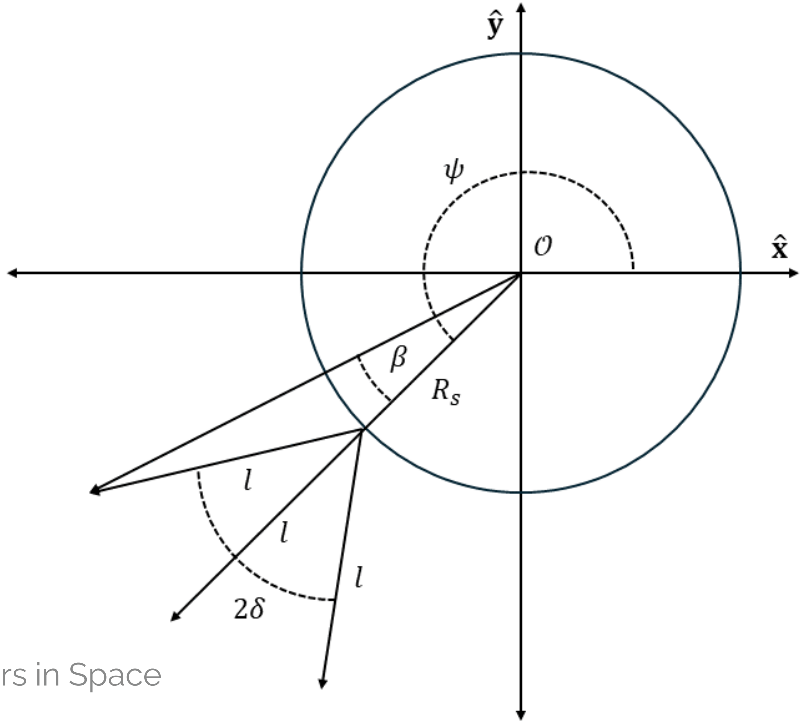
l = tether length

ψ = angle from positive x-axis to maneuver midpoint

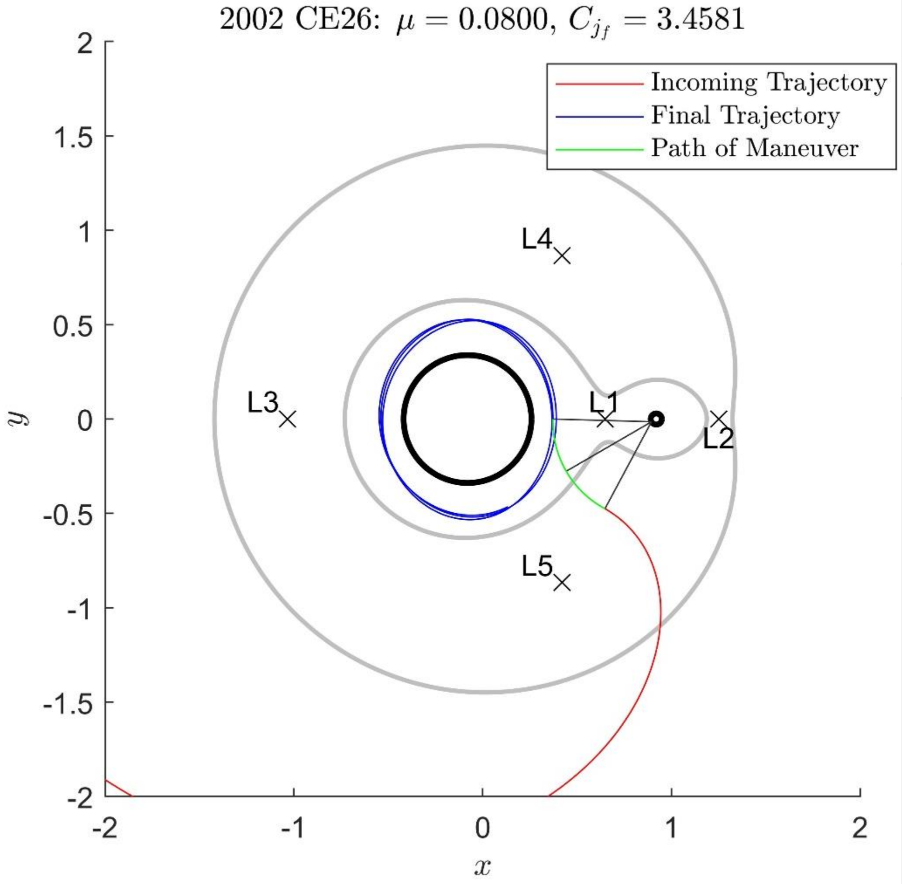
β = angle from midpoint to tether attachment/detachment (about origin)

δ = angle from midpoint to tether attachment/detachment (about tether attachment on asteroid surface)

v_∞ = magnitude of velocity of spacecraft entering asteroid system

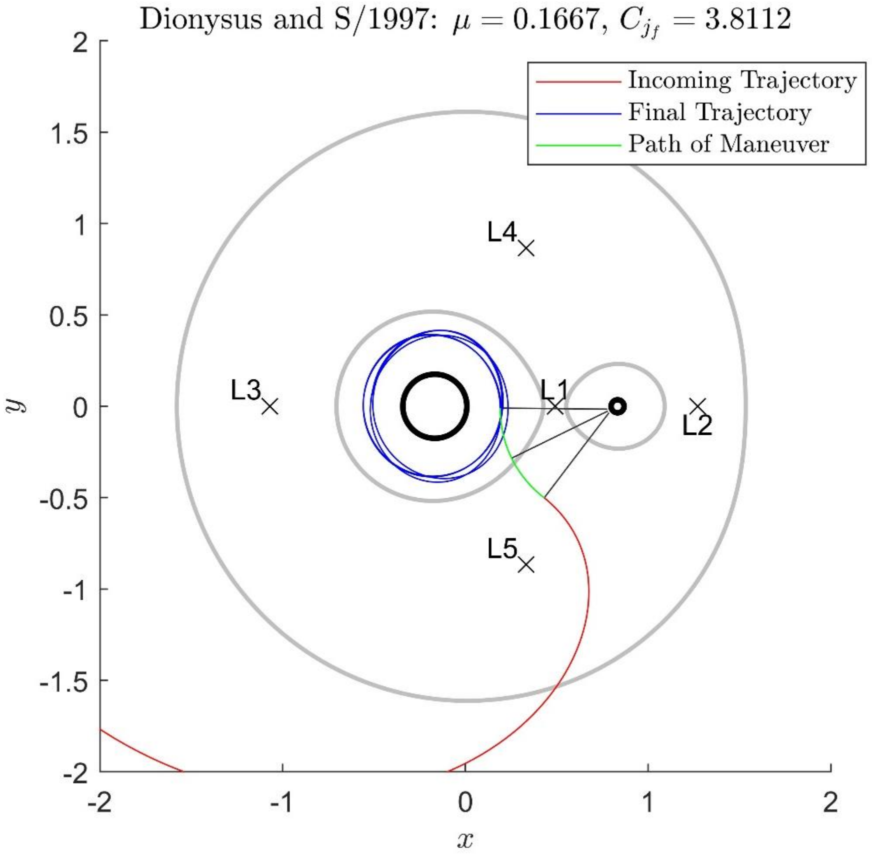


2002 CE26



Optimized tethered maneuver in 2002 CE26		
Design Variables	Values	
ψ	210.12°	
δ	31.73°	
	Dimensionless	Dimensional
l	0.5221	2.67×10^3 m
$\vec{\mathbf{r}}_d$	$[0.3730, -3.98 \times 10^{-5}]^T$	$[1.91 \times 10^\wedge 3, -0.2033]^T$ m
$\vec{\mathbf{v}}_d$	$[-0.0211, 1.0540]^T$	$[-0.0121, 0.6020]^T$ m/s
Output Parameters	Values	
C_{j_i}	2.0166	
C_{j_f}	3.4581	
ΔC_j	1.4415	
	Dimensionless	Dimensional
$\vec{\mathbf{r}}_i$	$[0.6482, -0.4751]^T$	$[3.31 \times 10^3, -2.43 \times 10^3]^T$ m
$\vec{\mathbf{v}}_i$	$[-0.9151, 0.5234]^T$	$[-0.5227, 0.2990]^T$ m/s
$\vec{\mathbf{r}}_f$	$[0.3726, -6.48 \times 10^{-5}]^T$	$[1.91 \times 10^3, -0.3308]^T$ m
$\vec{\mathbf{v}}_f$	$[-1.25 \times 10^{-4}, 1.0542]^T$	$[-7.12 \times 10^{-5}, 0.6021]^T$ m/s

DIONYSUS & S/1997



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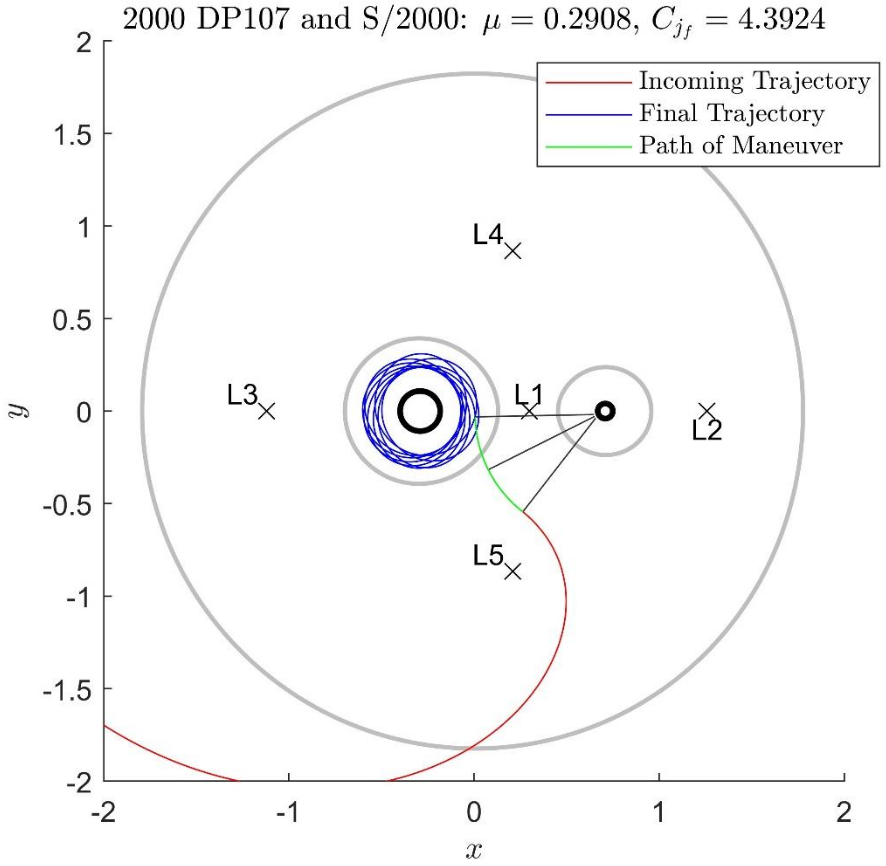
Optimized tethered maneuver in 2002 CE26		
Design Variables	Values	
ψ	206.11°	
δ	26.62°	
	Dimensionless	Dimensional
l	0.6099	2.49×10^3 m
$\vec{\mathbf{r}}_d$	$[0.1927, -9.36 \times 10^{-3}]^T$	$[786.33, -38.20]^T$ m
$\vec{\mathbf{v}}_d$	$[-0.1635, 1.2280]^T$	$[-0.0420, 0.3152]^T$ m/s
Output Parameters	Values	
C_{j_i}	1.6960	
C_{j_f}	3.8112	
ΔC_j	2.1152	
	Dimensionless	Dimensional
$\vec{\mathbf{r}}_i$	$[0.4320, -0.5010]^T$	$[1.76 \times 10^3, -2.04 \times 10^3]^T$ m
$\vec{\mathbf{v}}_i$	$[-0.9669, 0.7745]^T$	$[-0.2482, 0.1988]^T$ m/s
$\vec{\mathbf{r}}_f$	$[0.1915, -0.0102]^T$	$[781.47, -41.65]^T$ m
$\vec{\mathbf{v}}_f$	$[-0.0197, 1.2387]^T$	$[-5.06 \times 10^{-3}, 0.3180]^T$ m/s

2000 D107 & S/2000



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Optimized tethered maneuver in 2002 CE26		
Design Variables	Values	
ψ	206.64°	
δ	25.51°	
	Dimensionless	Dimensional
l	0.6662	2.46×10^3 m
$\vec{\mathbf{r}}_d$	$[0.0671, 4.74 \times 10^{-3}]^T$	$[247.70, 17.50]^T$ m
$\vec{\mathbf{v}}_d$	$[-0.1765, 1.1621]^T$	$[-0.0270, 0.1776]^T$ m/s
Output Parameters	Values	
C_{j_i}	1.8426	
C_{j_f}	4.3924	
ΔC_j	2.5498	
	Dimensionless	Dimensional
$\vec{\mathbf{r}}_i$	$[0.2641, -0.5442]^T$	$[975.61, -2.01 \times 10^3]^T$ m
$\vec{\mathbf{v}}_i$	$[-0.9099, 0.7442]^T$	$[-0.1390, 0.1137]^T$ m/s
$\vec{\mathbf{r}}_f$	$[6.84 \times 10^{-3}, -0.0313]^T$	$[25.28, -115.75]^T$ m
$\vec{\mathbf{v}}_f$	$[-0.0524, 1.1743]^T$	$[-8.00 \times 10^{-3}, 0.1794]^T$ m/s