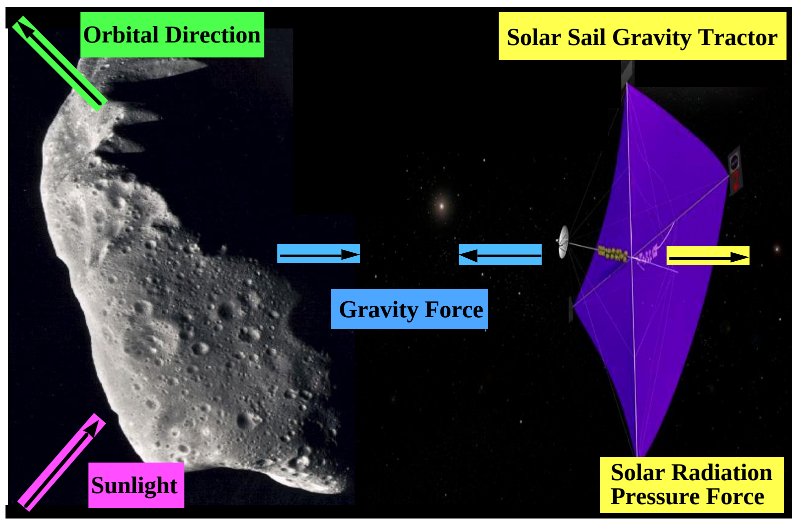
Hovering Control of a Solar Sail Gravity Tractor for Asteroid Deflection

Bong Wie
Dept. of Aerospace Engineering
Iowa State University
bongwie@iastate.edu
www.aere.iastate.edu



Previously Presented at
AAS/AIAA Space Flight Mechanics Meeting (Paper AAS 07-145)
2007 Planetary Defense Conference: Protecting Earth from Asteroids

Presentation Outline

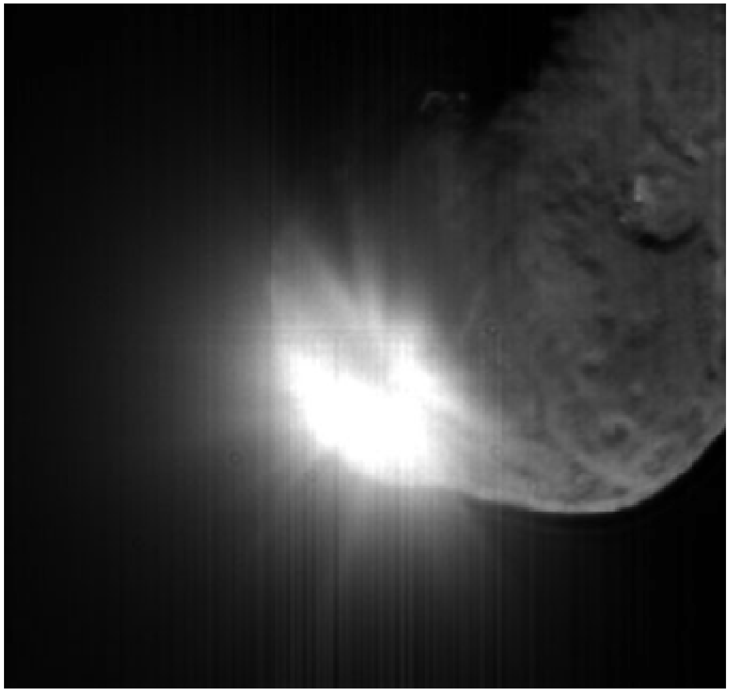
- **Kinetic Energy Impactor (KEI) Approach**
- **Gravity Tractor (GT) Concept by Lu and Love**
- **Solar Sail Gravity Tractor (SSGT) Options**
- **GT/SSGT Hovering Control Problem Formulation**
- **Engineering Analysis, Design, and Simulation**
- **Conclusion: KEI versus GT/SSGT**

Deep Impact Mission (July 4, 2005)

Not a Head-On Collision

The 5-km comet crashed into a 370-kg impactor resulting in a rear-end collision at 10 km/s impact speed

60-sec Before Impact



13-sec After Impact

Image Credit: NASA/JPL-Caltech/UMD

ESA's Don Quijote Mission for a 500-m NEA (Impactor Hidalgo and Orbiter Sancho)

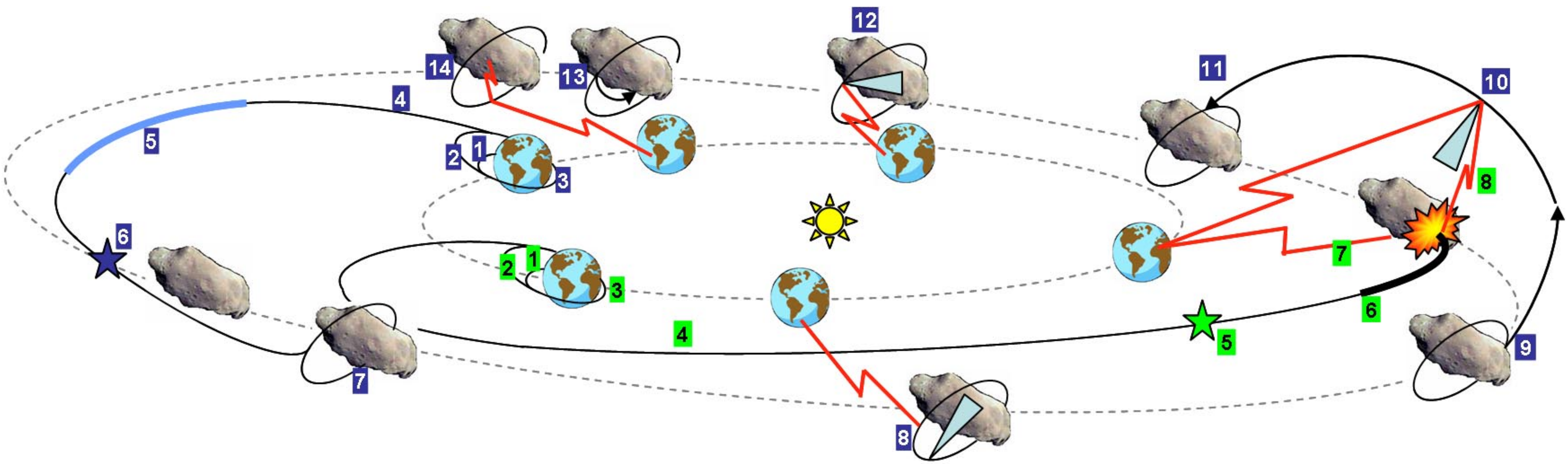


Image Credit: ESA

Schweickart, R., Lu, E., Hut, P., and Chapman, C., "The Asteroid Tugboat," ***Scientific American*****, November 2003.**

200-m, 10B-kg asteroid, 2.5-N thrust (Isp = ?), 3-month push, 1-cm/s ($\Rightarrow$ 0.58-cm/s) ΔV, 12-year coast, 6720-km ($\Rightarrow$ 2195-km)

B612 FOUNDATION

The Gravity Tractor

Vol 438 |10 November 2005 nature

BRIEF COMMUNICATIONS

Gravitational tractor for towing asteroids

A spacecraft could deflect an Earth-bound asteroid without having to dock to its surface first.

We present a design concept for a spacecraft that can controllably alter the trajectory of an Earth-threatening asteroid by using gravity as a towline. The spacecraft hovers near the asteroid, with its thrusters angled outwards so that the exhaust does not impinge on the surface. This proposed deflection method is insensitive to the structure, surface properties and rotation state of the asteroid.

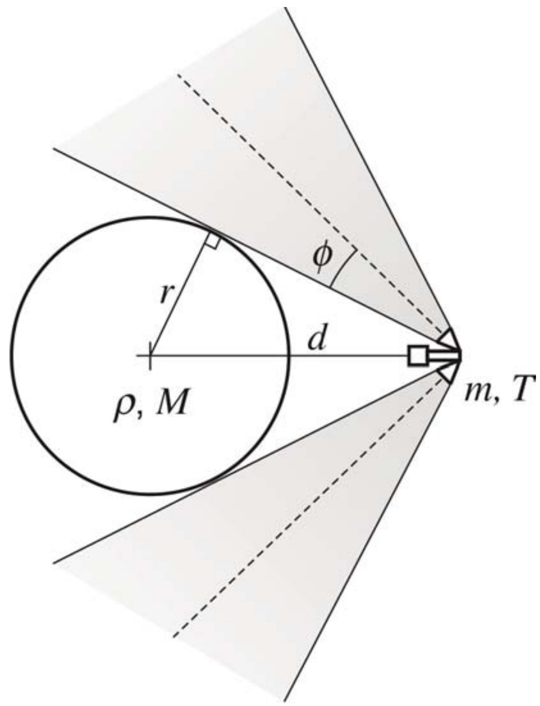
The collision of a small asteroid of about 200 m with the Earth could cause widespread damage and loss of life[1]. One way to deflect an approaching asteroid is to dock a spacecraft to the surface and push on it directly[2]. The total impulse needed for rendezvous and

Mass appeal: a spacecraft could use gravity to tow bodies away from a collision course with Earth.

D. DURDA, FIAAA/B612 FOUNDATION

Image Credit: B612 Foundation

Engineering Analysis of the Gravity Tractor Concept for Towing Asteroids



$$M\frac{\Delta V}{\Delta t} = \frac{GMm}{d^2} \leq T$$

where $G = 6.6695 \times 10^{-11}$ N-m^2/kg^2, $M = 46$B kg (320-m Apophis), $m = 1000$ kg, $d = 1.5r = 240$ m, $T = 0.053$ N, and

$$\frac{\Delta V}{\Delta t} = \frac{Gm}{d^2} = \frac{T}{M} = A = 1.157 \times 10^{-9} \text{ mm/s}^2 \text{ (<< the Yarkovsky effect ???)}$$

- The orbital "amplification" effects:

$$\Delta V \approx 3A(\Delta t) \Rightarrow 0.1 \text{ mm/s for one-year towing}$$

$$\Delta X \approx \frac{3}{2}A(\Delta t)^2 \Rightarrow 1.7 \text{ km for one-year towing}$$

$$\begin{aligned}\text{Final } \Delta X &\approx \frac{3}{2}A(\Delta t)(\Delta t + 2t_c) \\ &= (3/2)A(\Delta t)^2 + \Delta V t_c \\ &\Rightarrow 1.7 \text{ km } + 10.3 \text{ km} \\ &\Rightarrow 12 \text{ km for } t_c = 3 \text{ years} \\ &\Rightarrow \text{sufficient to miss a 600-m keyhole}\end{aligned}$$

- Xenon propellant consumption:

$$\Delta m_f = \frac{2T\Delta t}{g_o I_{sp}} \approx 0.3 \text{ kg per day } \approx 114 \text{ kg per year}$$

where $T = 0.053$ N, $g_o = 9.8$ m/s^2, and $I_{sp} = 3000$ sec

• The low-thrust Gravity Tractor (GT) is probably applicable only to NEOs with the special astrodynamic property of "keyholes and resonant returns."

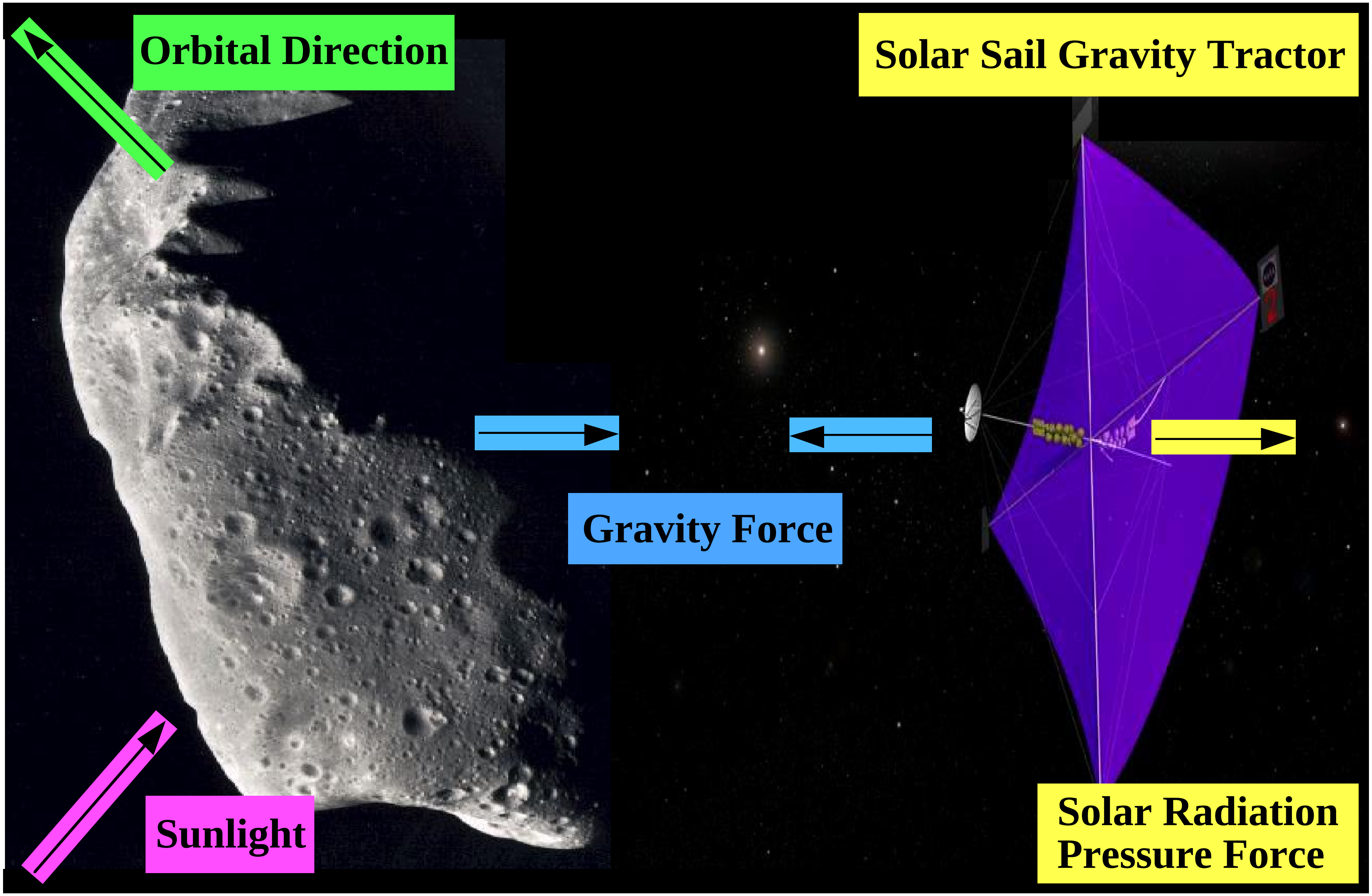
• A conventional KEI mission can easily produce a sufficient impact ΔV to move Apophis out of its small keyhole in 2029.

• A conventional KEI mission (but with multiple impactors) can also be employed for NEOs without the special property of "keyholes and resonant returns."

• How about highly porous, rubble pile asteroids without keyholes and resonant returns ?

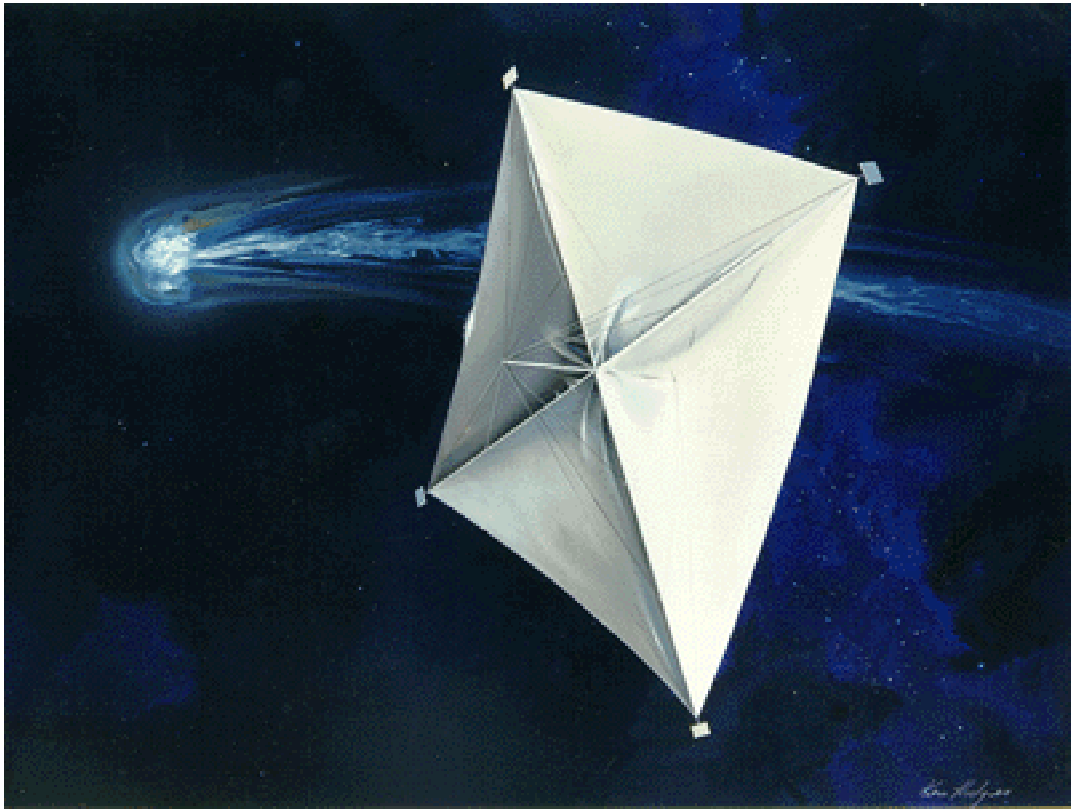
• T = 0.053 N, Isp = 3,000 sec, m = 1,000 kg, 10-year towing $\Rightarrow \Delta V = 0.1$ cm/s and $\Delta m_f = 1{,}140$ kg

Solar Sail Gravity Tractor



Solar sails are very large, lightweight reflectors in space that are pushed by sunlight, and ±35-deg tack angle is used to increase/decrease orbital energy

⇒ "Propellantless" Propulsion Systems



A Large Solar Sail for an Asteroid Deflection (?) Mission

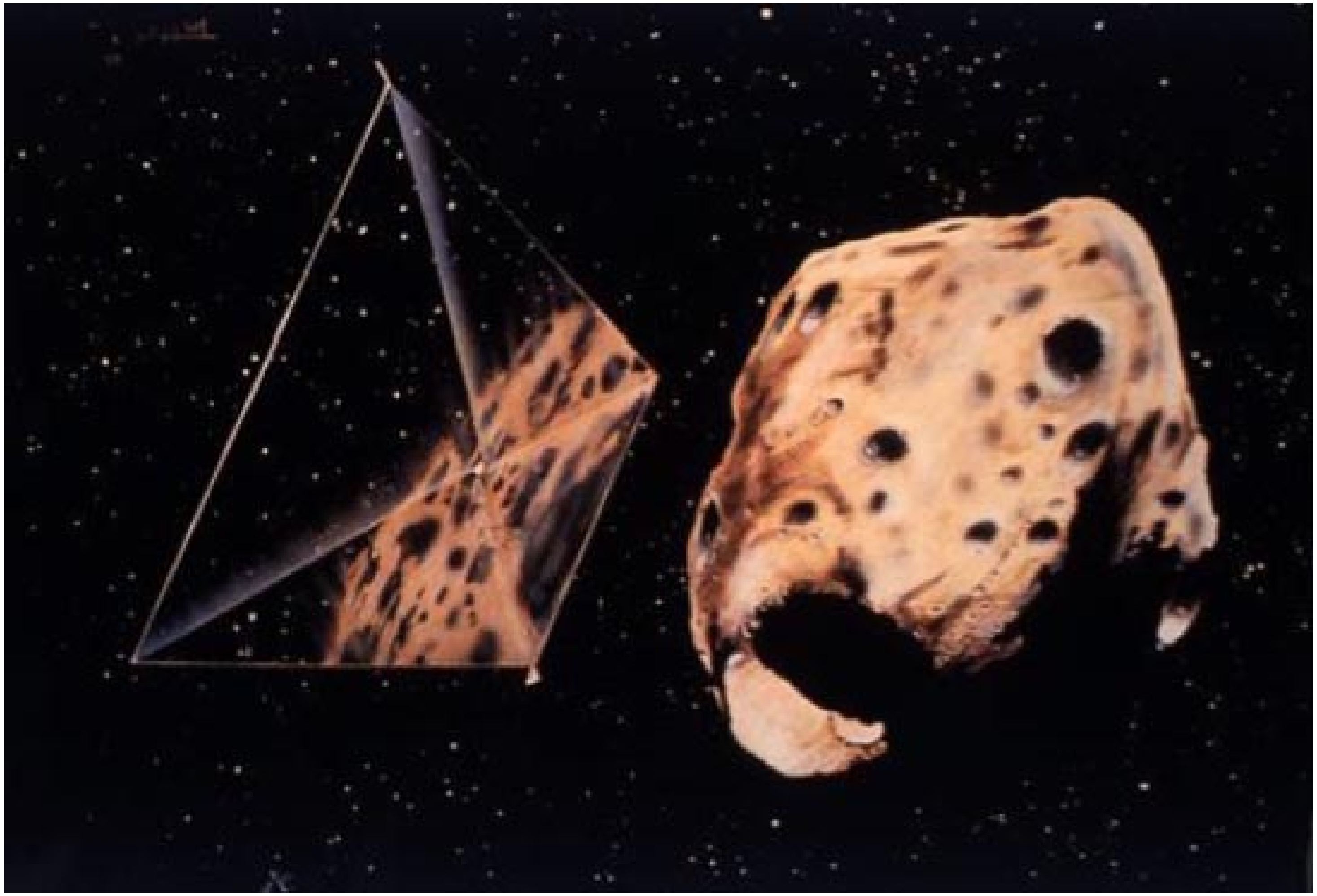
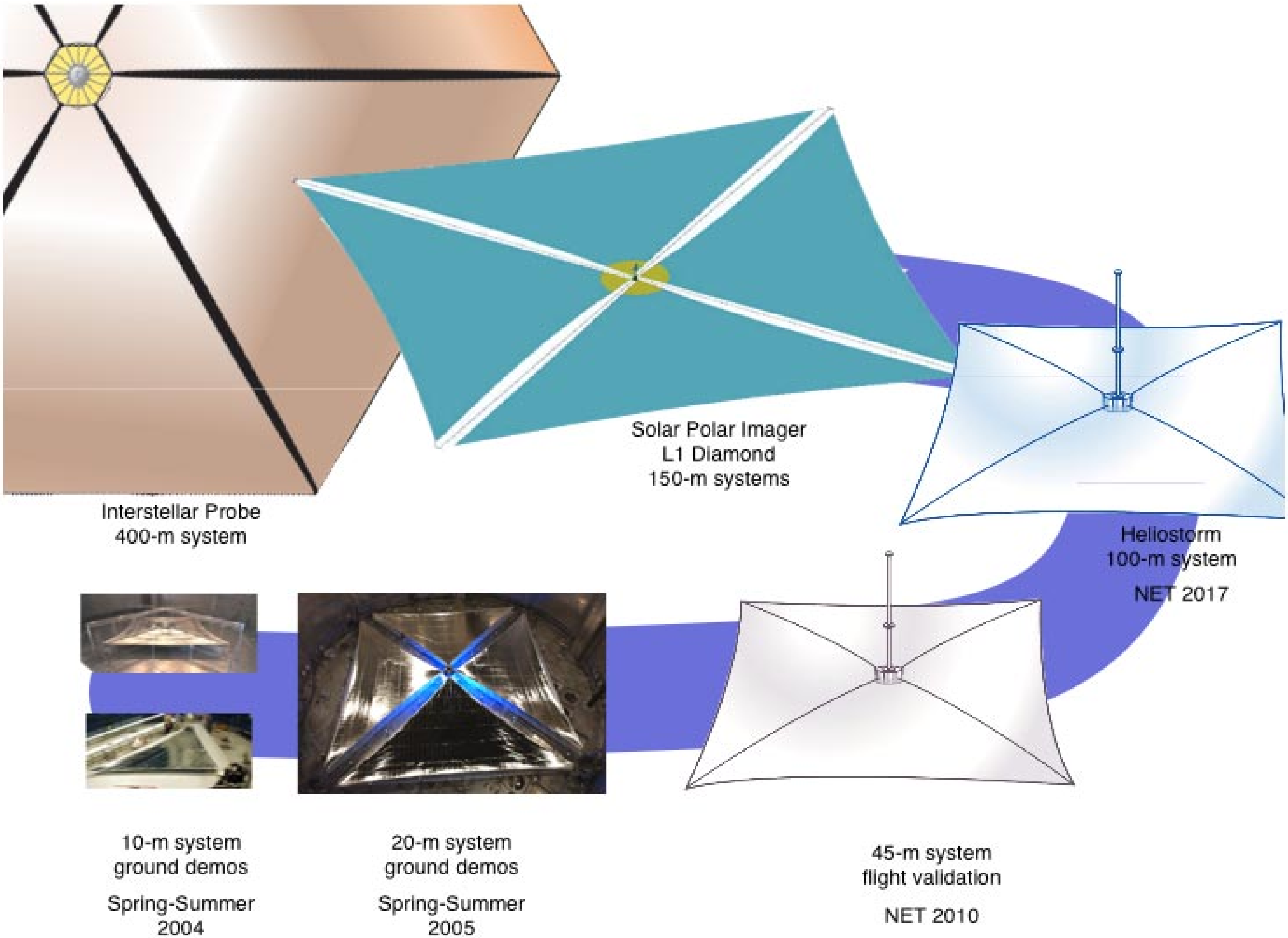


Image Credit: U3P

NASA's Solar Sail Roadmap

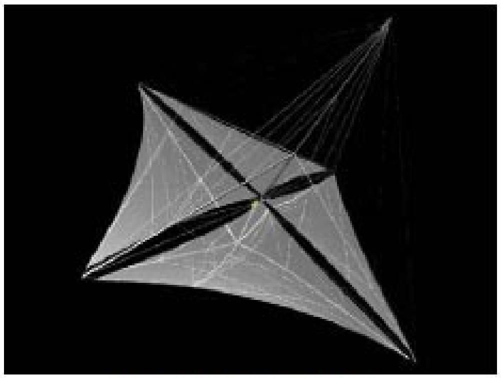


Cosmos 1 (30 m, 105 kg) Flight Experiment: 6/21/05

Courtesy of The Planetary Society (L. Friedman) and NPO Lavochkin

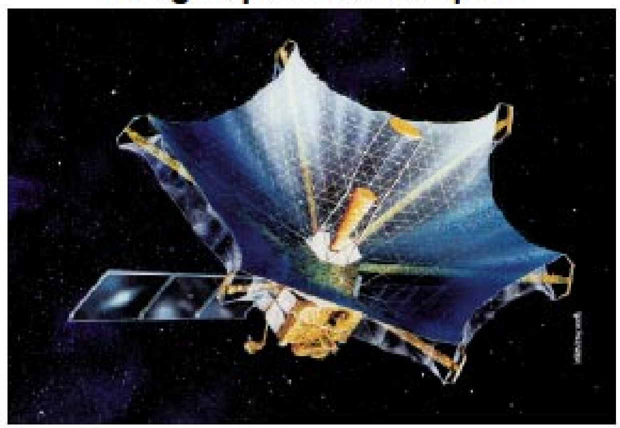
NMP ST9 Solar Sail Flight Validation Opportunity (Final Selection in Spring 2007)

ST9 Technology Capability Areas

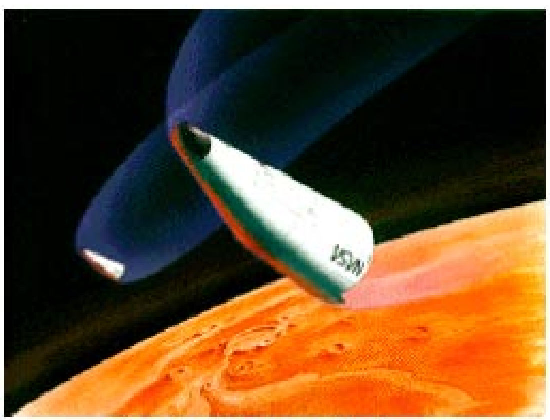


Solar Sail Flight System Technology

System Technology for Large Space Telescopes



Precision Formation Flying System Technology



Aerocapture System Technology for Planetary Missions

8/16/04

<u>Future Applications</u>

Solar Sail
L1-Diamond
Solar Polar Imager

Formation Flying
TPF, MAXIM, Stellar Imager

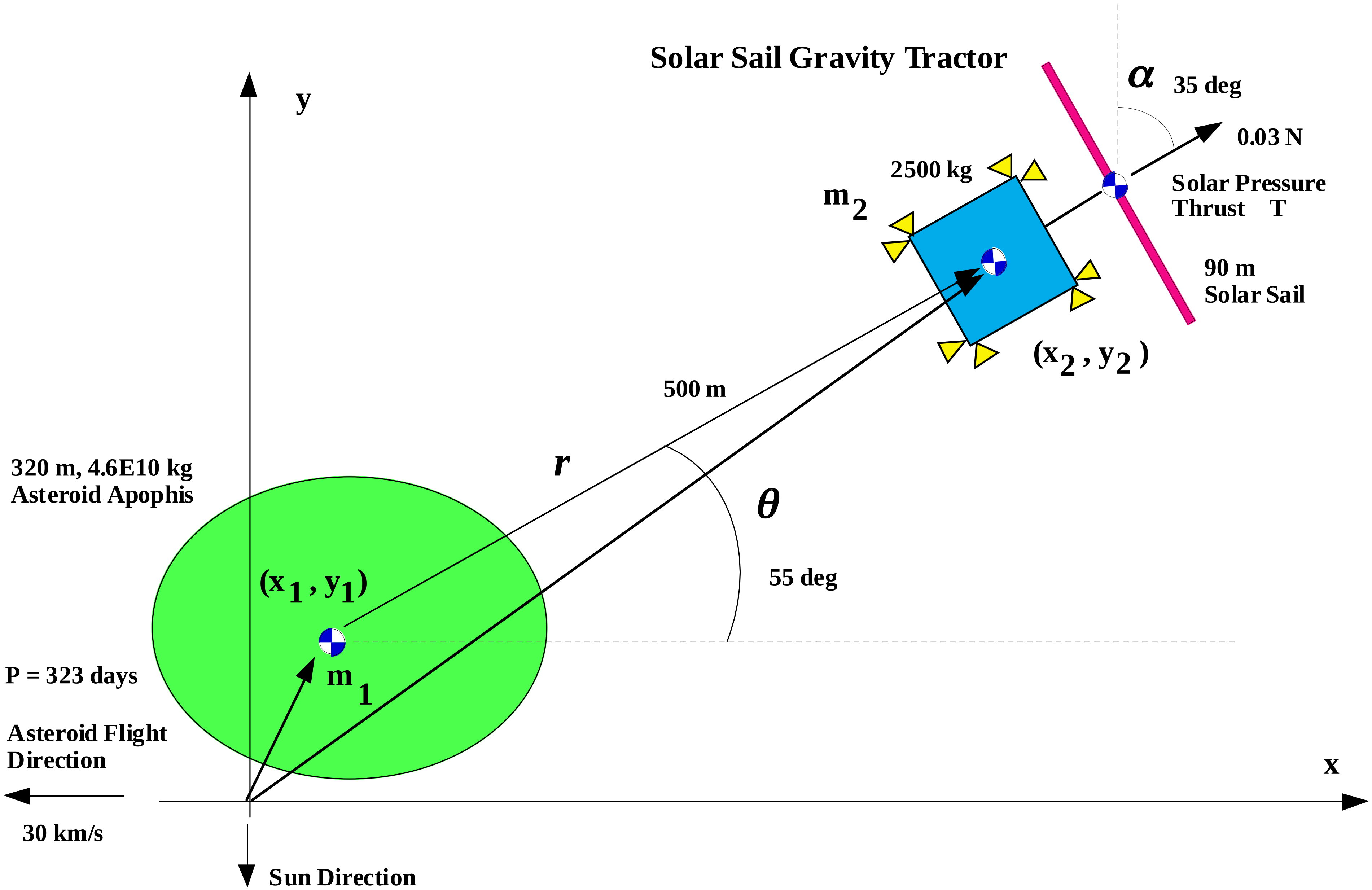
Large Space Telescopes
SAFIR, TPF, Life Finder

Terrain-Guided Automatic Landing System (TGALS)
MSL, Europa Lander, Mars Sample Return

Aerocapture
Orbiter Missions at Bodies with Atmospheres, e.g. Titan, Venus, Mars, Neptune

Descent and Terminal Guidance System Technology for Pinpoint Landing and Hazard Avoidance

Modeling and Control of Hovering GT/SSGT Spacecraft



$$\ddot{x}_1 = 2n\dot{y}_1 + Gm_2\frac{x_2 - x_1}{r^3}(1 + E_x)$$
$$\ddot{y}_1 = -2n\dot{x}_1 + 3n^2 y_1 + Gm_2\frac{y_2 - y_1}{r^3}(1 + E_y)$$
$$\ddot{x}_2 = 2n\dot{y}_2 - Gm_1\frac{x_2 - x_1}{r^3}(1 + E_x) + \frac{1}{m_2}(T_x + F_x)$$
$$\ddot{y}_2 = -2n\dot{x}_2 + 3n^2 y_2 - Gm_1\frac{y_2 - y_1}{r^3}(1 + E_y) + \frac{1}{m_2}(T_y + F_y)$$

$$E_x = 0.2\sin\omega t; \quad E_y = 0.2\cos\omega t$$
$$\tan\theta = \frac{y_2 - y_1}{x_2 - x_1}; \qquad \alpha = \pi/2 - \theta$$
$$T_x = T_o \cos^2\alpha \sin\alpha$$
$$T_y = T_o \cos^2\alpha \cos\alpha$$
$$x = x_2 - x_1 = r\cos\theta; \qquad y = y_2 - y_1 = r\sin\theta$$
$$F_x = -K_p(x - x_c) - K_d\dot{x}$$
$$F_y = -K_p(y - y_c) - K_d\dot{y}$$
$$\text{if } |F_x| > F_{max},\ F_x = \mathrm{sgn}(F_x)F_{max}$$
$$\text{if } |F_y| > F_{max},\ F_y = \mathrm{sgn}(F_y)F_{max}$$
$$\text{if } |x - x_c| < \epsilon_x,\ F_x = 0$$
$$\text{if } |y - y_c| < \epsilon_y,\ F_y = 0$$

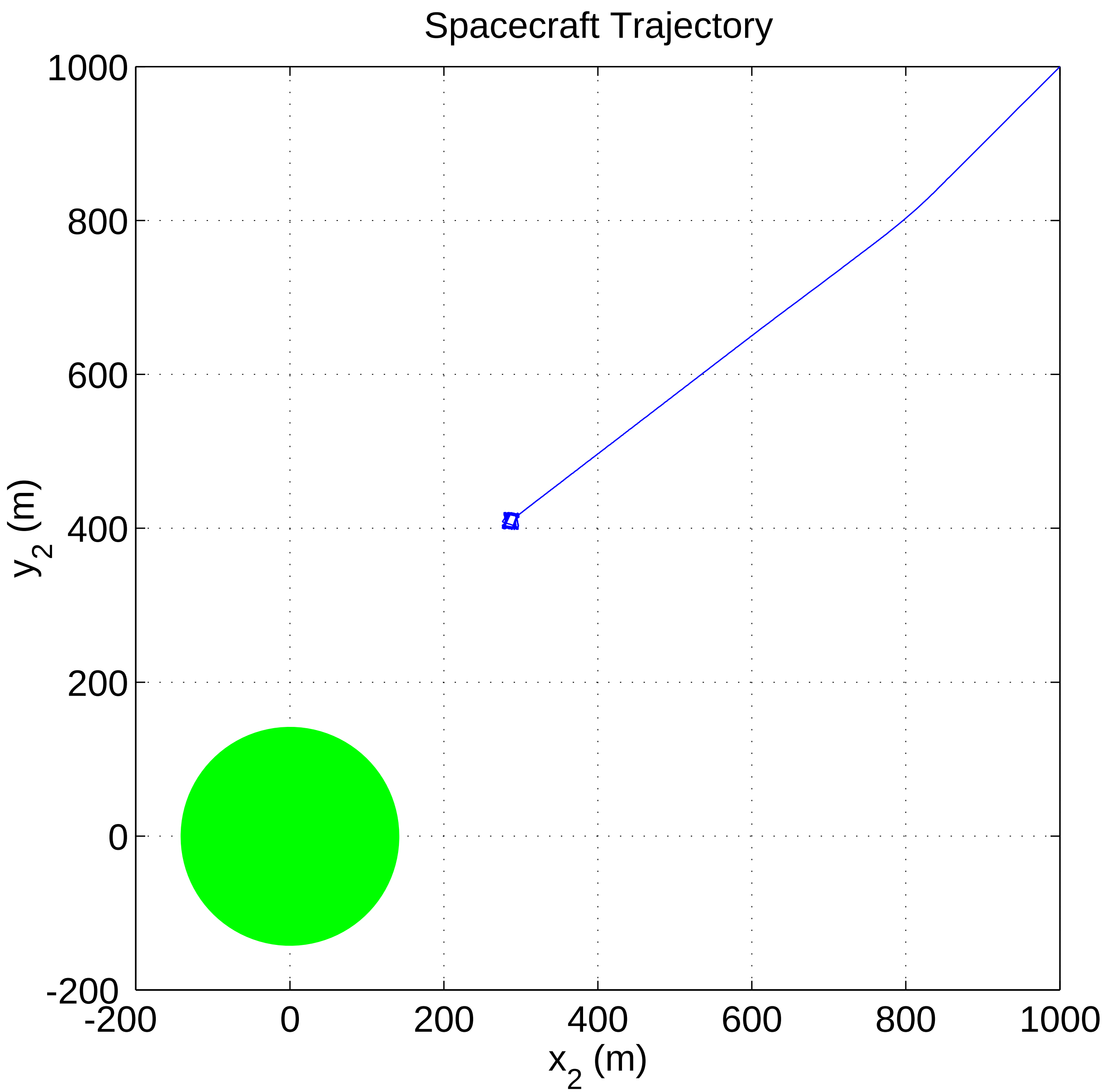


Figure 1: **Hovering control simulation results for Option 3 (Solar Sail Gravity Tractor). Starting point at (x, y) = (1000, 1000) m and a desired hovering point (x, y) = (286, 409) m.**

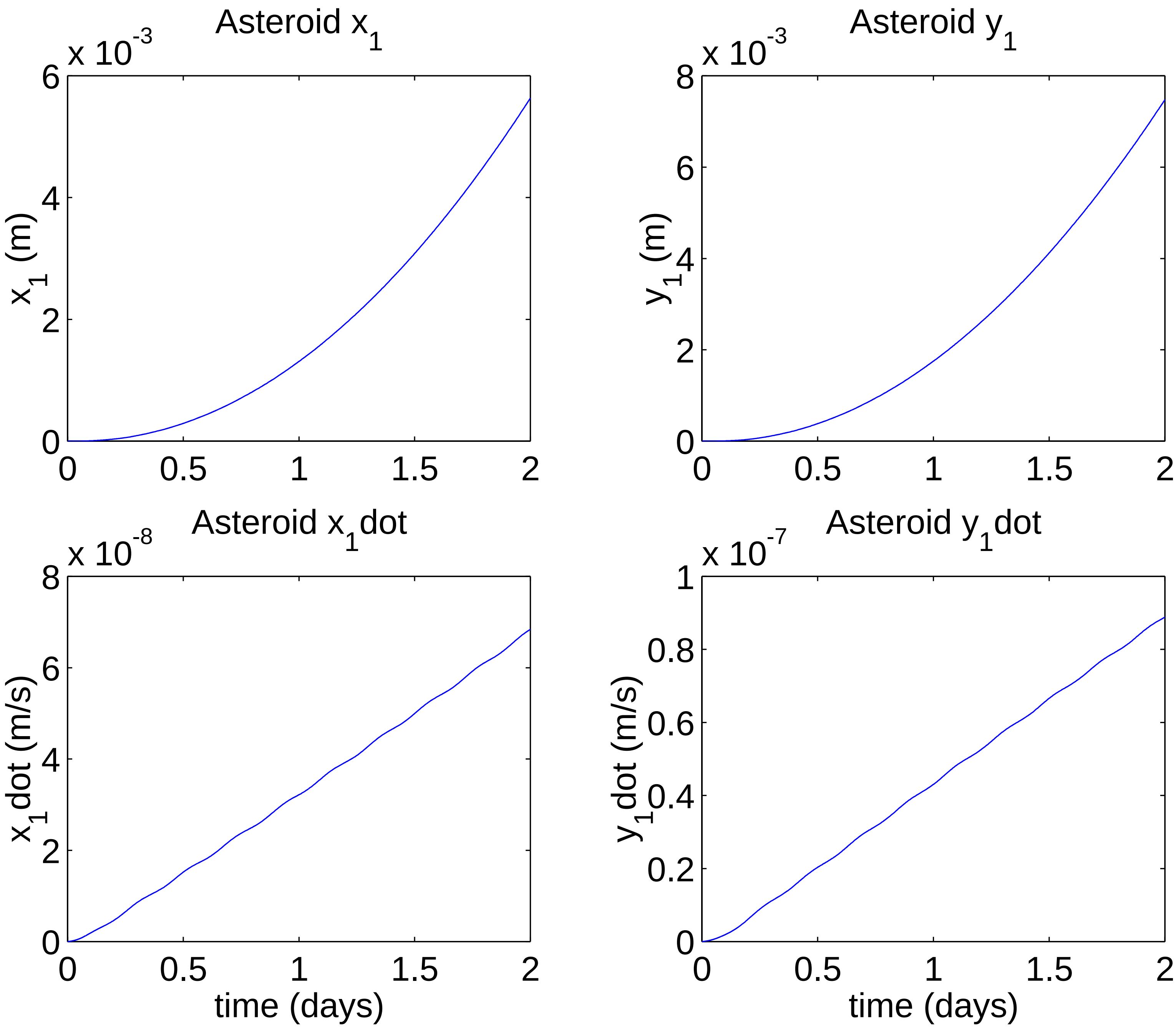


Figure 2: **Option 3 SSGT (continued).**

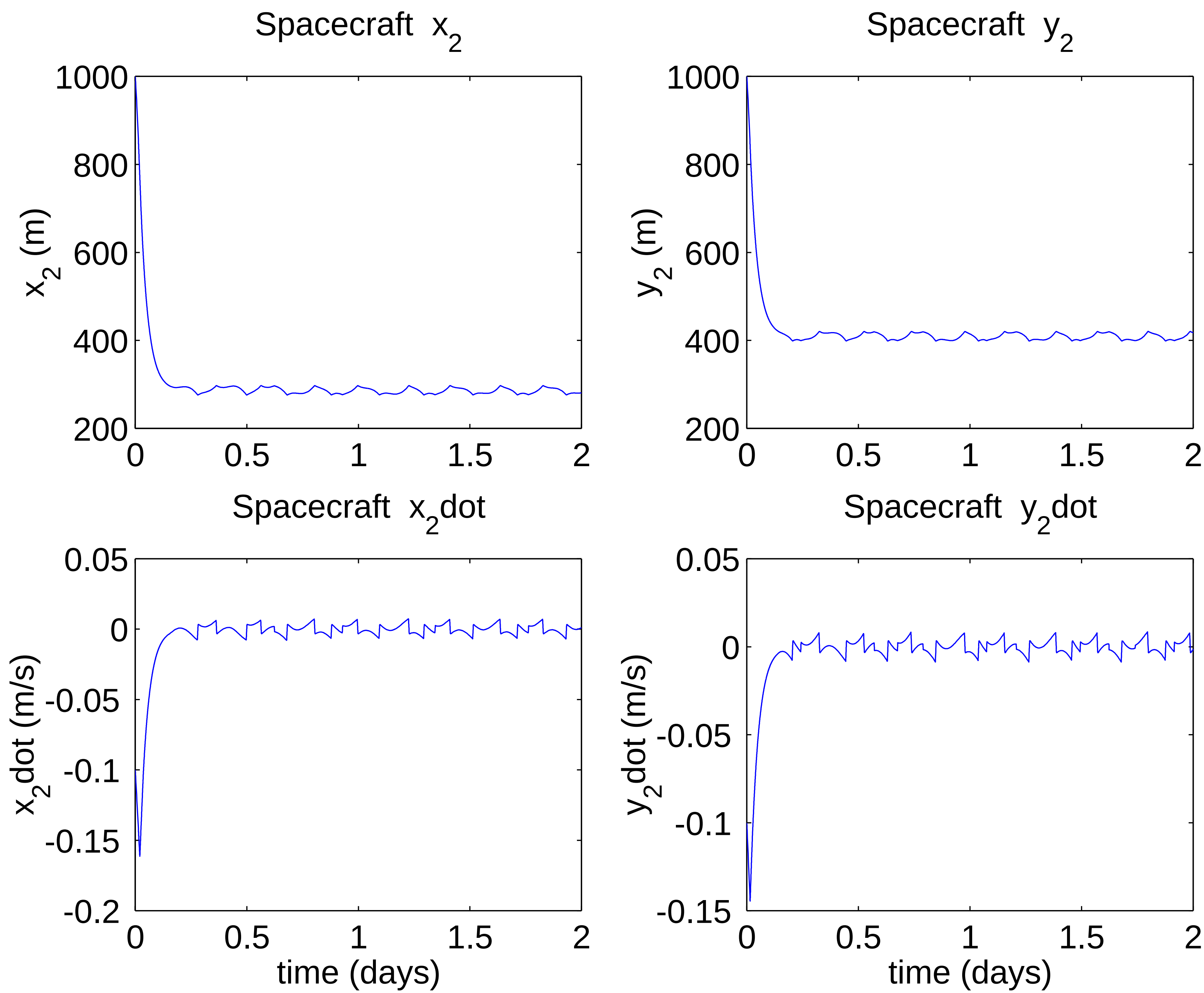


Figure 3: **Option 3 SSGT (continued).**

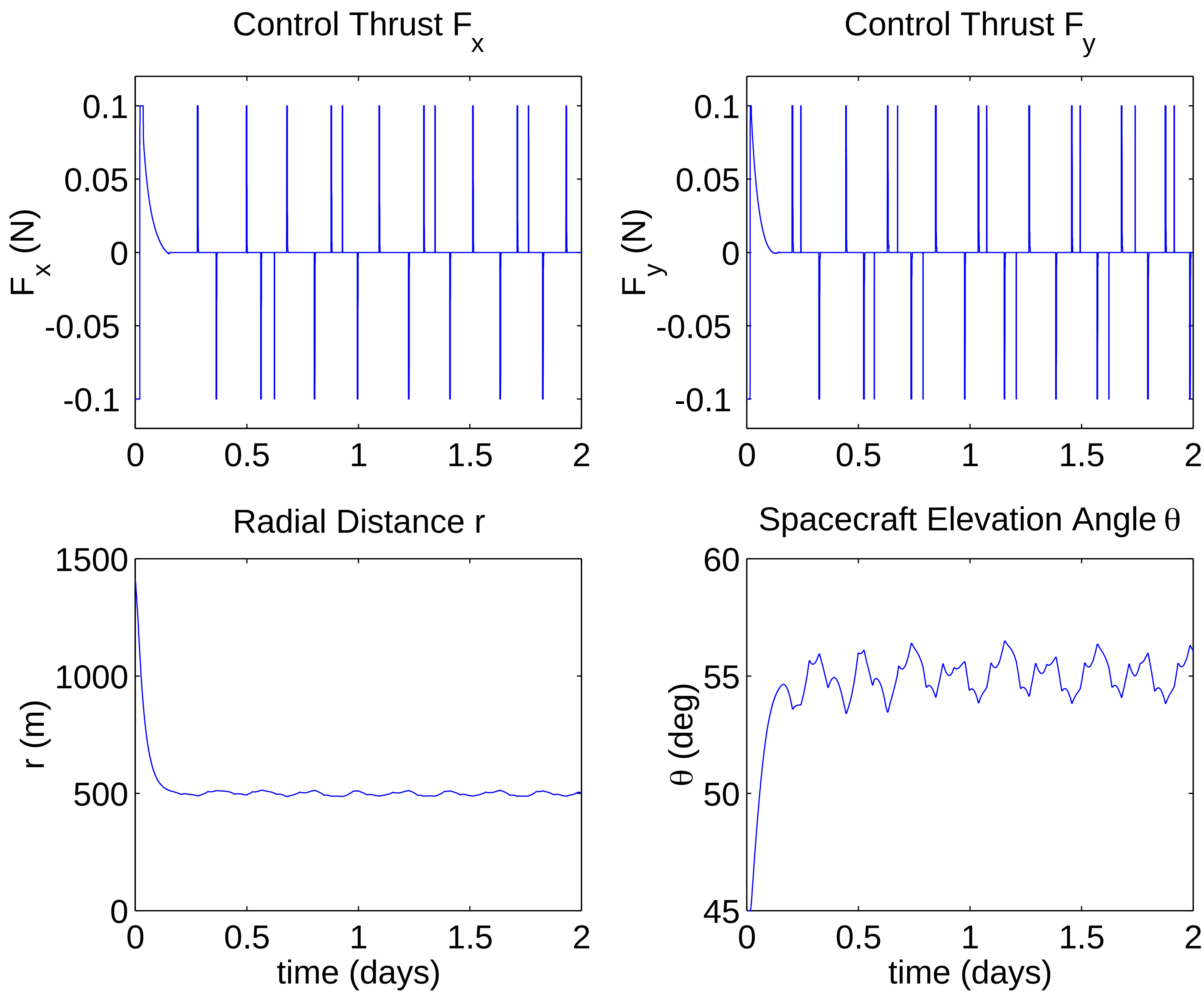


Figure 4: **Option 3 SSGT (continued).**

Asteroid Deflection Formula Using C-W-H Equations

$$\ddot{x} - 2n\dot{y} = A$$
$$\ddot{y} + 2n\dot{x} - 3n^2 y = 0$$

$$y(t) = -\frac{2}{n}\dot{x}(0)(1-\cos nt) - \frac{2}{n}A\left(t - \frac{1}{n}\sin nt\right)$$

$$\begin{aligned} x(t) &= -\dot{x}(0)\left(3t - \frac{4}{n}\sin nt\right) - \frac{3}{2}At^2 + \frac{4}{n^2}A(1-\cos nt) \\ &\approx -3\dot{x}(0)t - \frac{3}{2}At^2 \end{aligned}$$

$$\Delta x = x_0 + \dot{x}_0\left(\frac{4}{n}\sin nt_c - 3t_c\right) + 6y_0(nt_c - \sin nt_c) - \frac{2\dot{y}_0}{n}(-1+\cos nt_c)$$
$$\Delta y = -\frac{2\dot{x}_0}{n}(1-\cos nt_c) + y_0(4 - 3\cos nt_c) + \frac{\dot{y}_0}{n}\sin nt_c$$
$$\Rightarrow \Delta x = -\frac{3}{2}At_a(t_a + 2t_c) = -\left(\frac{3}{2}At_a^2 + \Delta V t_c\right) \text{ where } \Delta V = 3At_a$$

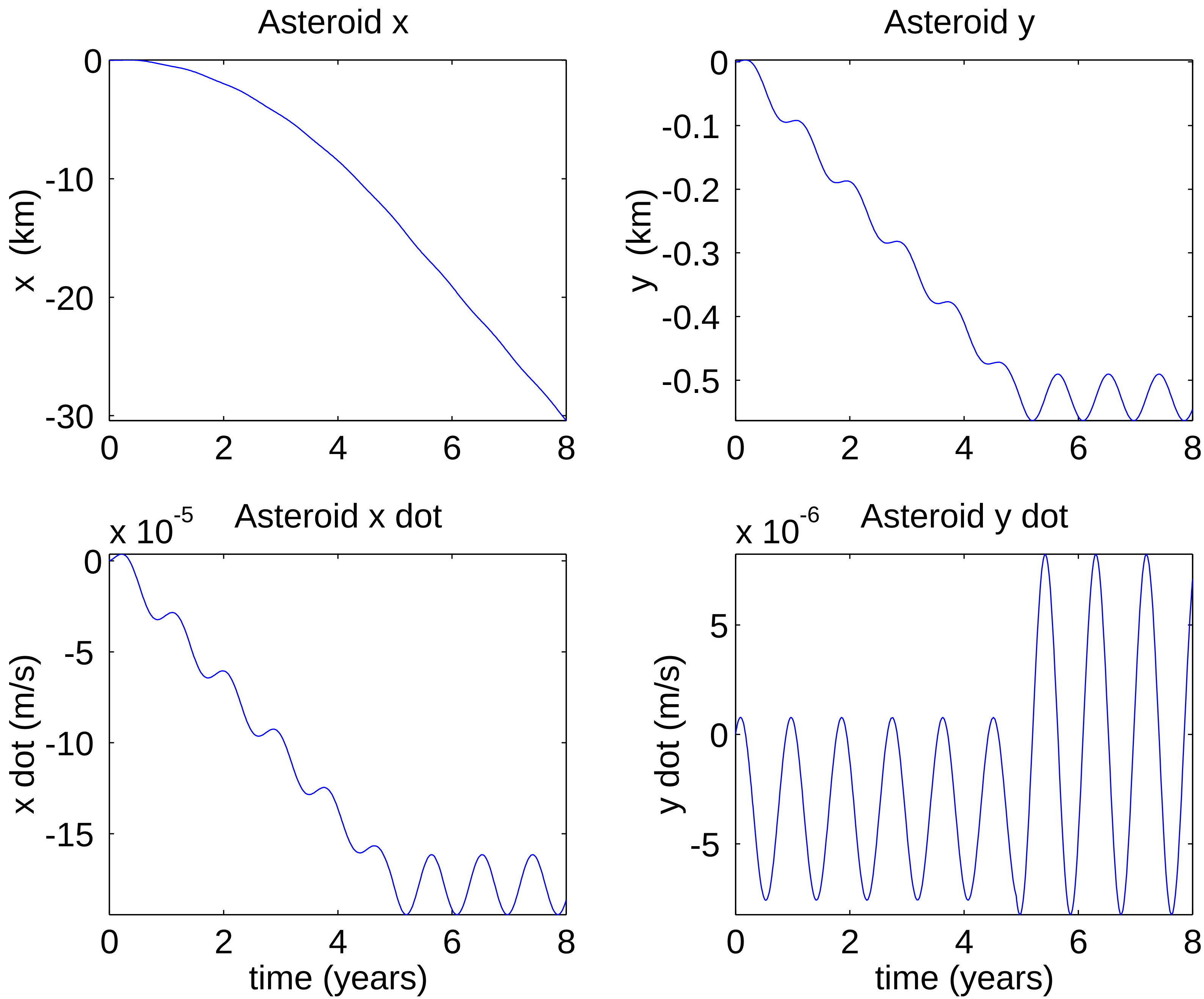


Figure 1: **Long-term simulation of a 2500-kg SSGT ($t_a = 5$ years, and $t_c = 3$ years).**

Asteroid Deflection Formula Summary

- **For Kinetic Energy Impactors:**

$$\Delta V = \eta \frac{m}{M} V_{impact} \quad \Rightarrow \quad \Delta X = 3 \Delta V t_c$$

- **For Low-Thrust GT/SSGT:**

$$\Delta V = 3 A t_a \;\; \text{where} \;\; A = \frac{T}{M}$$

$$\begin{aligned} \Delta X &= (3/2) A t_a^2 + 3 \Delta V t_c - 2 \Delta V t_c \\ &= (3/2) A t_a^2 + \Delta V t_c \\ &\approx \Delta V t_c \quad \text{(less deflection due to gravity loss)} \end{aligned}$$

The Asteroid Tugboat Example (*Scientific American*, November 2003): 200-m, 10B-kg asteroid, 2.5-N thrust, 3-month push, 1-cm/s (⇒ 0.58-cm/s) ΔV, 12-year coast, 6720-km (⇒ 2195-km) deflection

Eccentricity Effect

Apophis: e = 0.19 and a = 0.92239 AU

$$\ddot{x} = 2\dot{\theta}\dot{y} + \ddot{\theta}y + \dot{\theta}^2 x - \frac{\mu}{r^3}x + A_x$$

$$\ddot{y} = -2\dot{\theta}\dot{x} - \ddot{\theta}x + \dot{\theta}^2 y + \frac{2\mu}{r^3}y + A_y$$

$$\ddot{r} = r\dot{\theta}^2 - \frac{\mu}{r^2}$$

$$\ddot{\theta} = -\frac{2\dot{r}\dot{\theta}}{r}$$

$$r = \frac{p}{1 + e\cos\theta} = \frac{a(1 - e^2)}{1 + e\cos\theta}$$

$$\dot{r} = \sqrt{\mu/p}\,(e\sin\theta)$$

$$\dot{\theta} = \sqrt{\mu/p^3}\,(1 + e\cos\theta)^2$$

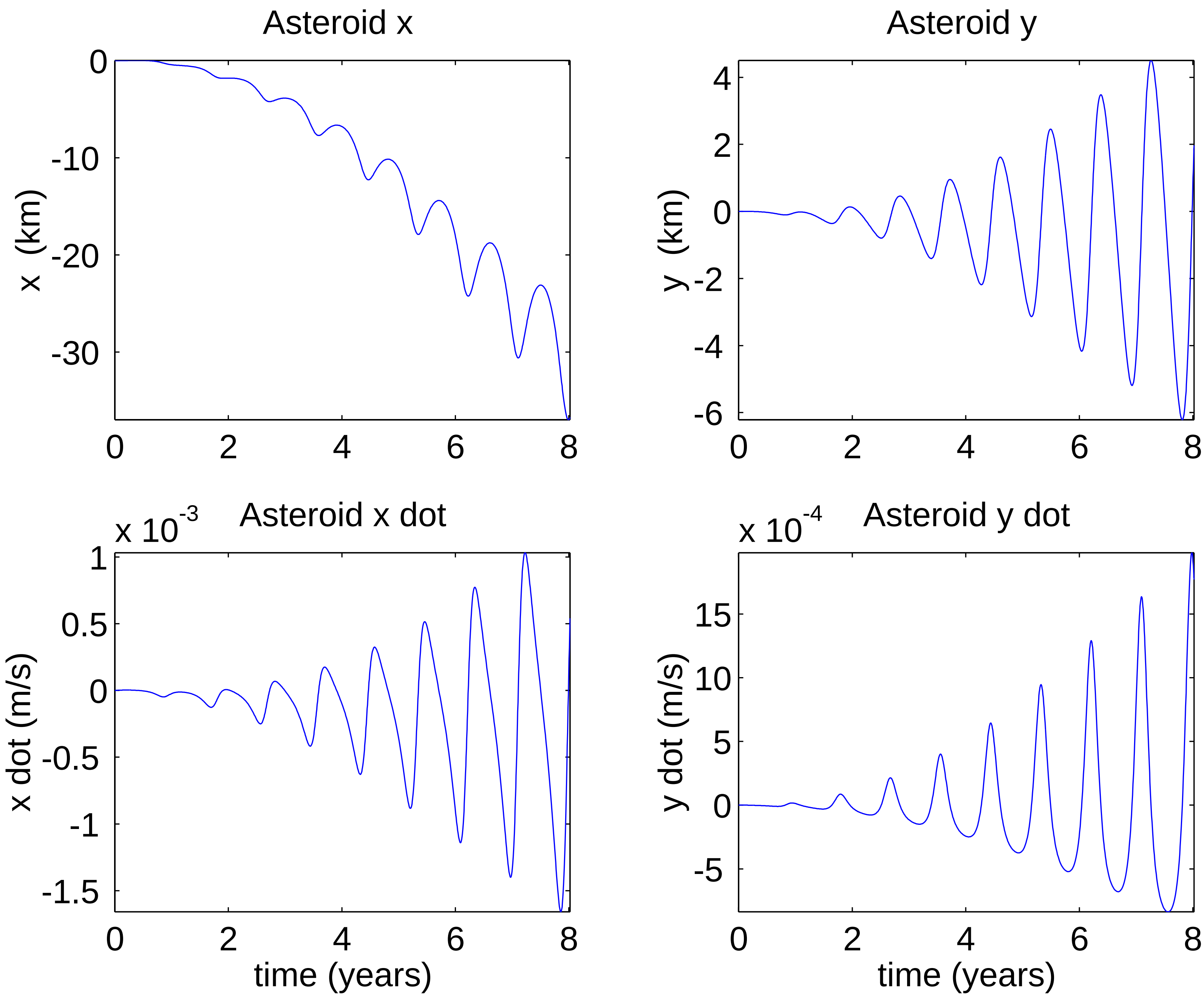


Figure 2: **Long-term simulation for Apophis with $e = 0.19$, $t_a = 5$ years ,and $t_c = 3$ years.**

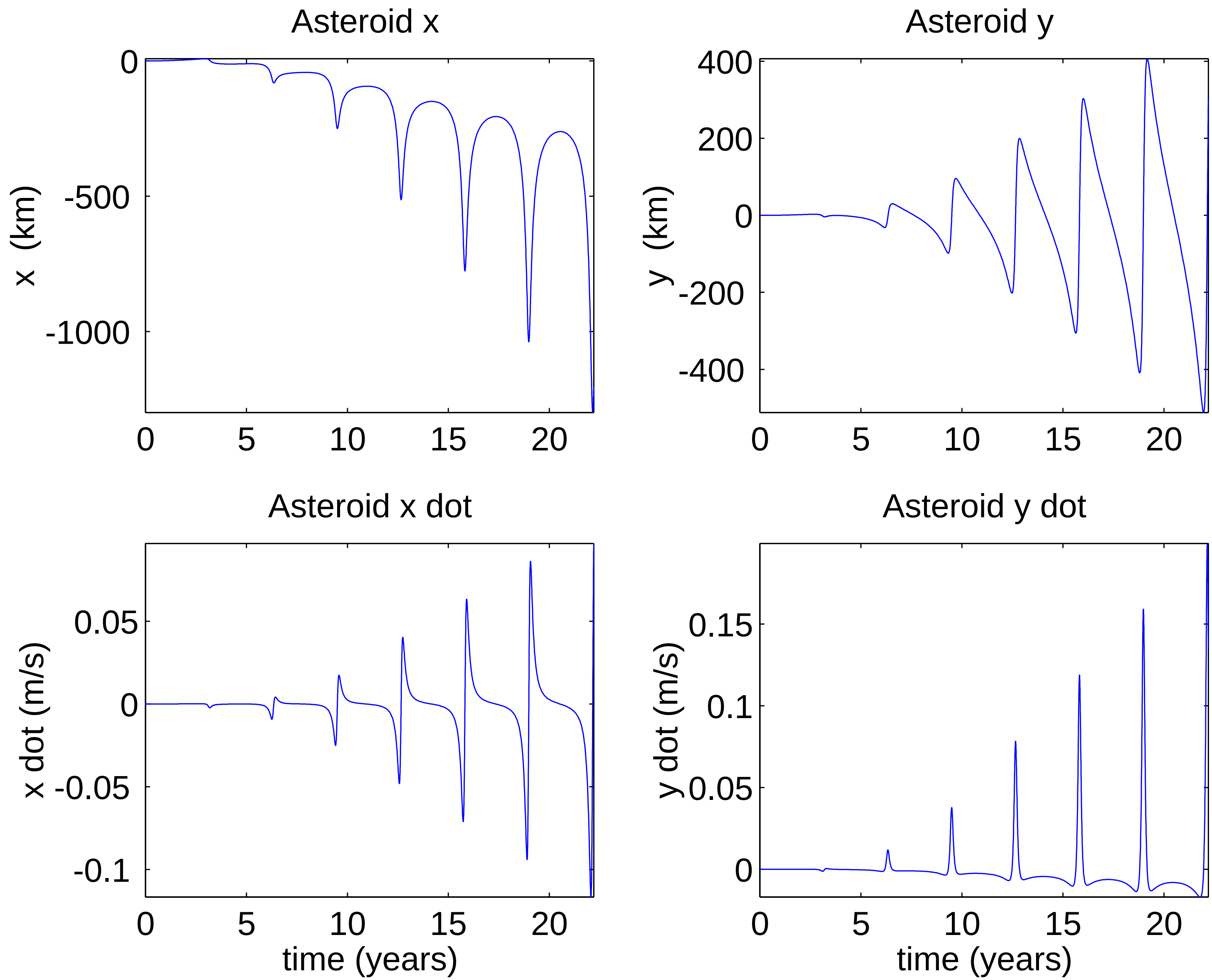
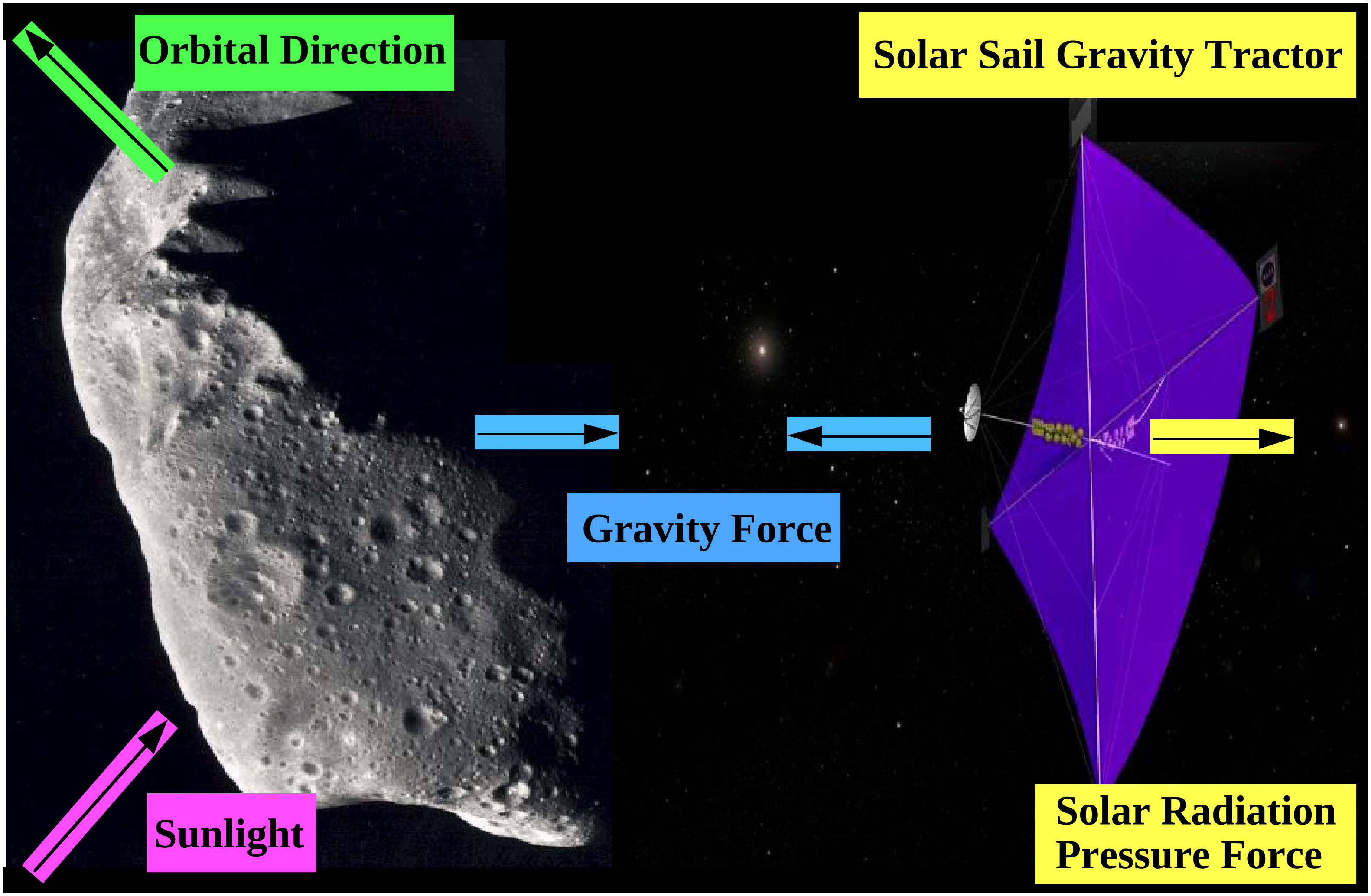
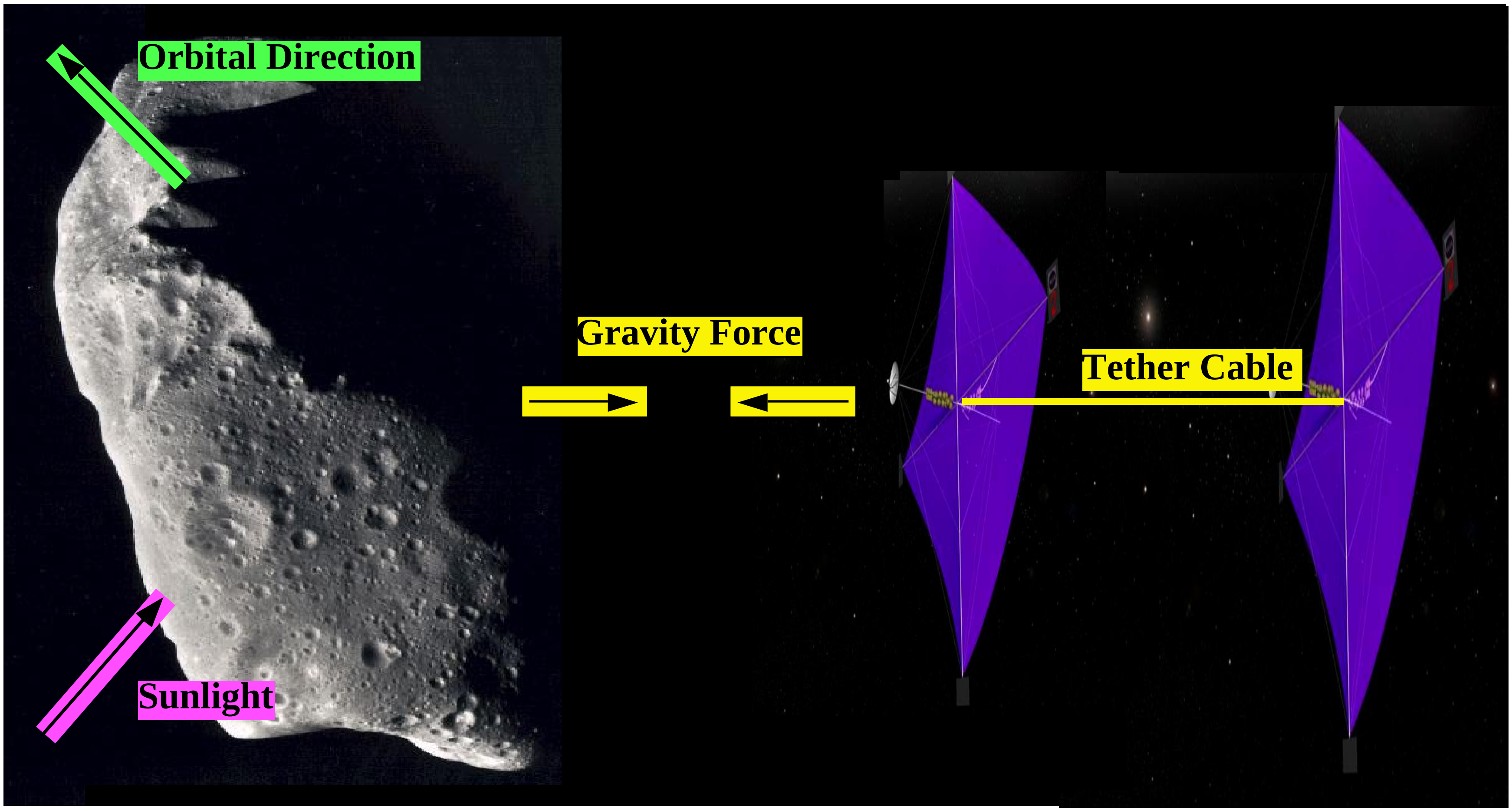


Figure 3: **Long-term simulation a 200-m asteroid with $M = 1.1 \times 10^{10}$ kg, $a = 2.1537$ AU, $e = 0.6498$, $A_x = 1.76 \times 10^{-9}$ mm/s^2, $A_y = 2.51 \times 10^{-9}$ mm/s^2, $t_a = 10$ years, and $t_c = 12$ years.**

Conclusions: KEI versus GT/SSGT



Asteroid Deflection Using a Gravity Tractor with Tethered Solar Sails



The Space Tow Concept by Gyula Greschik