A Multi-Satellite Mission to Illuminate the Earth: Formation Control Based on Impulsive Maneuvers

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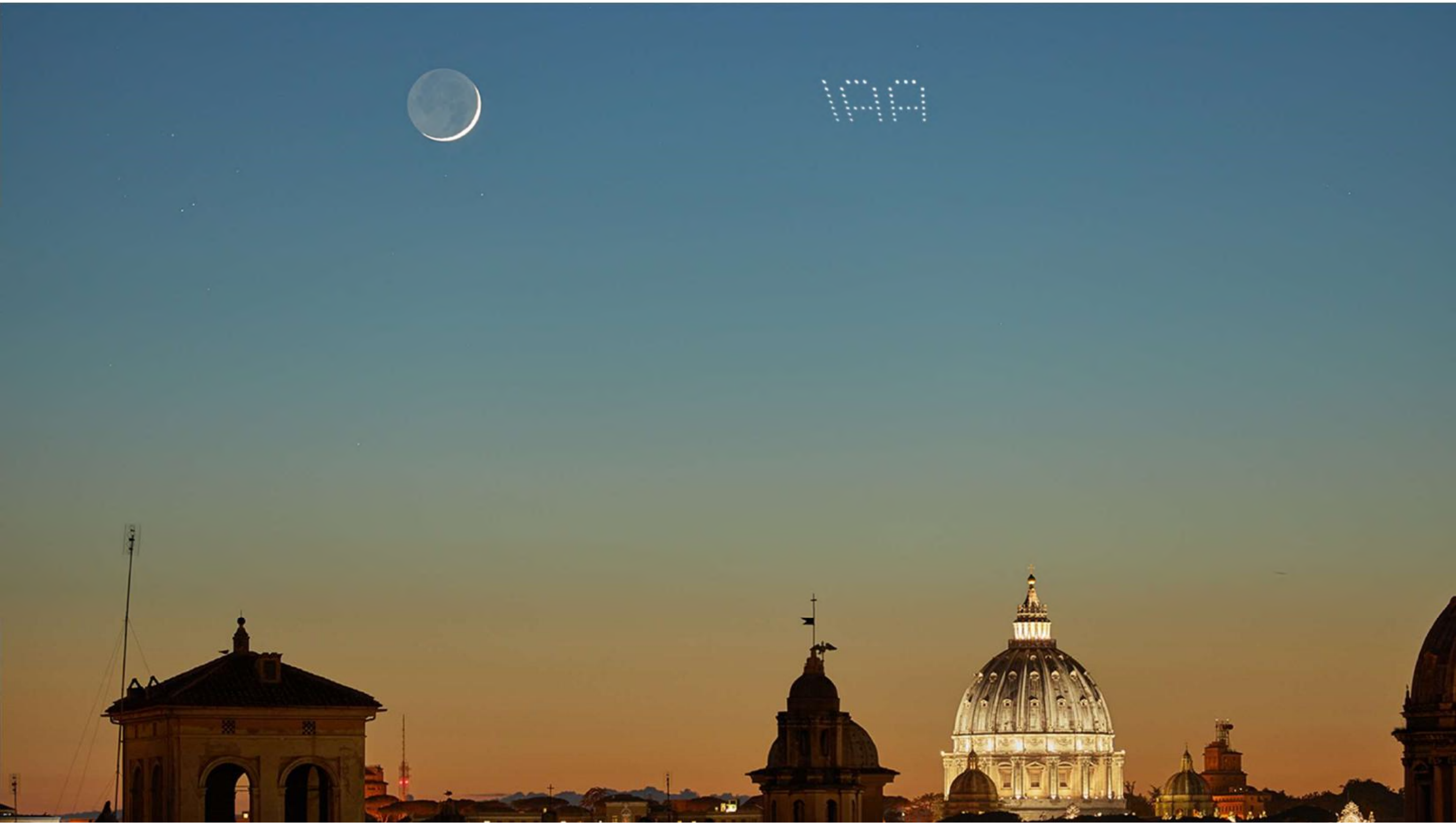
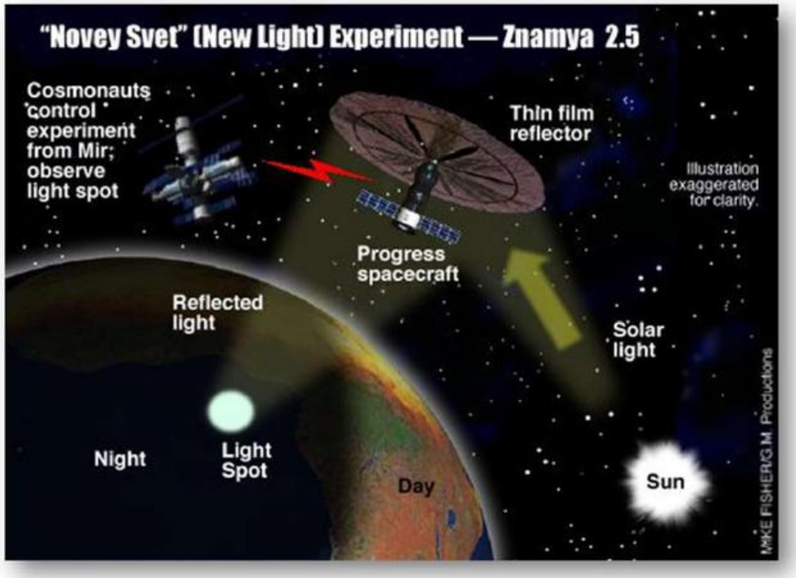


History

The idea of a mirror in space to reflect sunlight and thus generate power and light on Earth was proposed in 1928 by Hermann Oberth who postulated a space-manufactured 5mm thick mirror using sodium for the reflective layer, orbiting Earth at 1000-5000 km altitude



The first practical step towards this end was the Russian Space Mirror Project ‘‘Znamya’’ launched in 1992 which was to illuminate high latitude Earth regions during winter months using 20 meters width reflector

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Designing sunlight reflector

Requirements for image demonstration:

- Line of sight **POI** ↔ **Satellite** & **Sun** ↔ **Satellite**;
- The magnitude **m ~ -8.0** or brighter;
- The elevation angle of the Sun at the POI **ϒ < -5°**;
- The angular distance between two adjacent satellites shall be greater than 1 arcminute [1];

Parametric model for sunlight reflector:

- Target orbit and POI on Earth;
- Reflector physical parameters;

Reflector area

1. Yanoff, Myron, and Jay S. Duker. "Opthalmology." (2009).

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Spacecraft visibility

We define **spacecraft's visibility** in terms of magnitude:

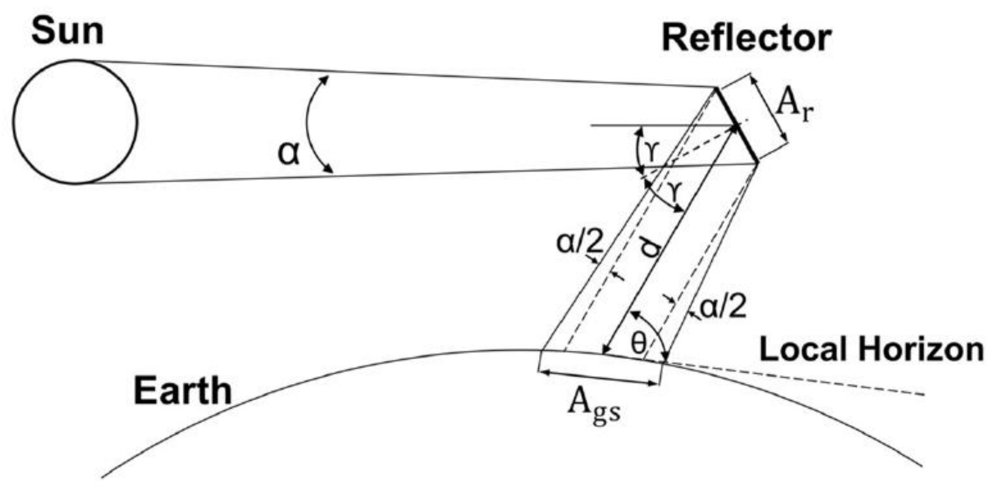
$$m = -2.5\ \mathrm{Log}\left(\frac{I}{I_{ref}}\right);$$

The intensity of the light at the POI is given by [2]:

$$I = \frac{I_0 A_r \rho \tau \cos(\gamma) \sin(\theta)}{4d^2 \left(\tan\left(\frac{\alpha}{2}\right)\right)^2},$$

where atmospheric transmissivity $\boldsymbol{\tau}$ is given by [2]:

$$\tau = 0.1283 + 0.7559e^{-0.3778\ \sec(\pi/2-\theta)}$$



- α – included angle of the Sun measured from the Earth;
- d – spacecraft to ground spot distance;
- A_r – area of the CubeSat reflector;
- A_{gs} – area of the ground spot;
- θ – the elevation angle of the spacecraft;
- γ – the incident angle of solar rays;
- I_0 – average intensity of solar energy at the Earth distance;
- ρ – reflectivity coefficient;

2. Canady Jr, John E., and John L. Allen Jr. "Illumination from space with orbiting solar-reflector spacecraft." (1982).

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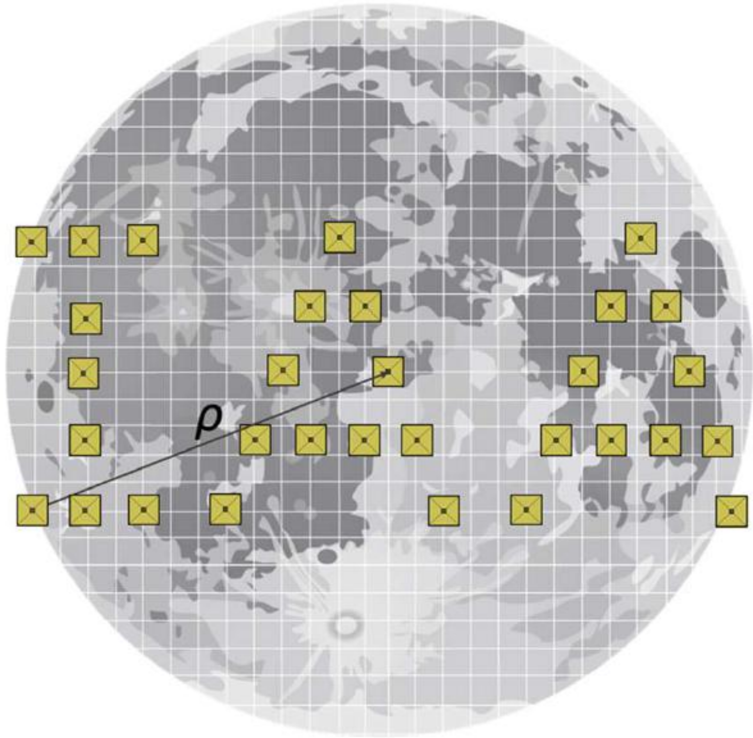
Mission design

Time of demonstration: 30 Jan 2020, 17:54:00 Italy time
(when formation is at zenith)

Name	Value	Reason
Altitude	**700 km**	**Lifetime**
Eccentricity	0	Circular
Inclination	**98.2°**	**SSO**
RAAN	**43.5°**	**Line of nodes ⊥ to Sun direction**
TA	42.2°	Flying over Rome
Image size	**6 km**	**Moon angular size**



Angular size of graphic image when is passes zenith
(ρ - angular size of the Moon)

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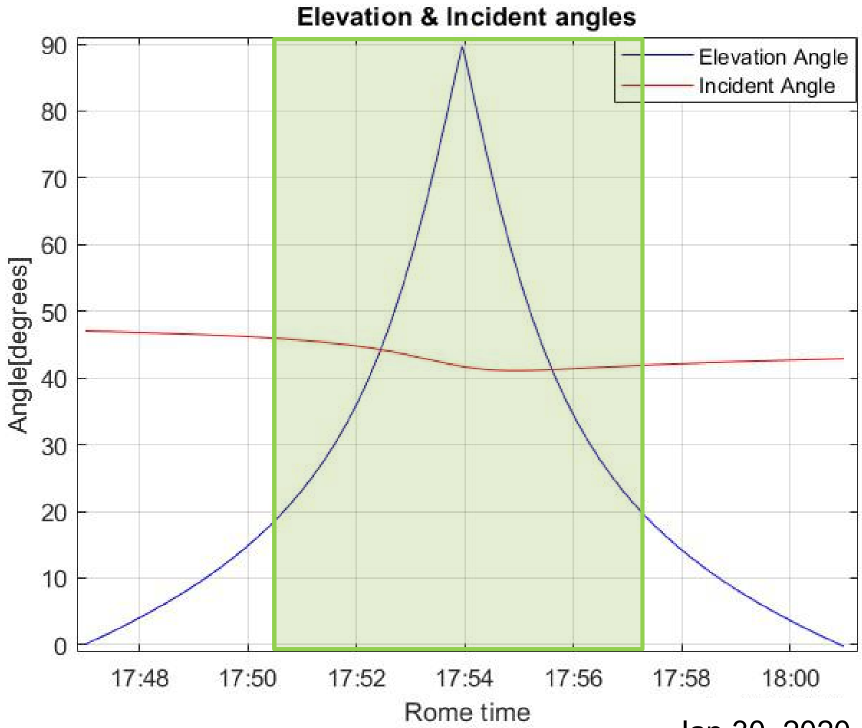
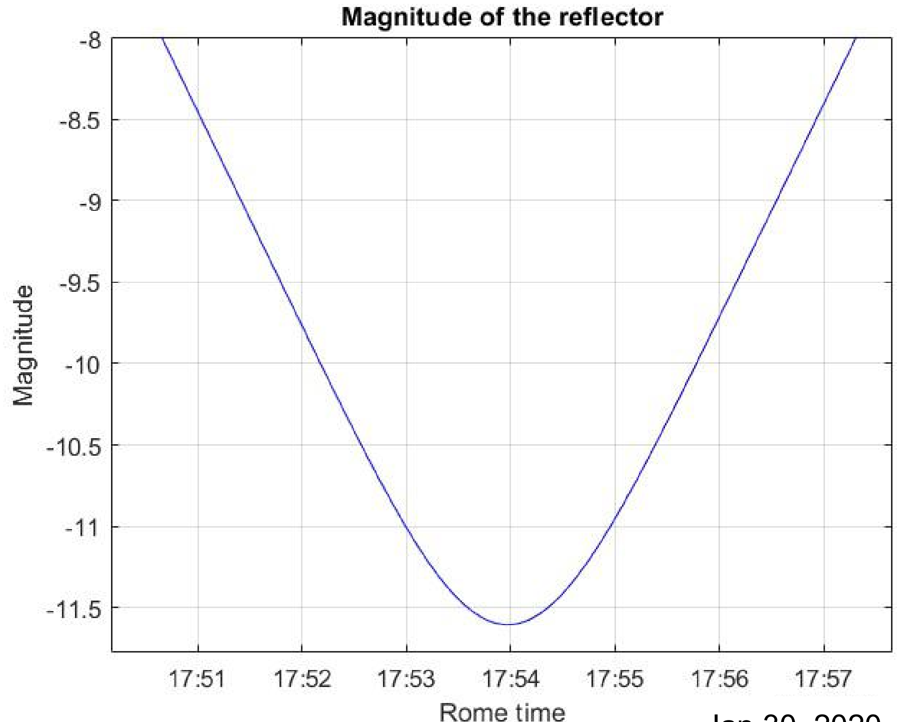
Demonstration parameters



Jan 30, 2020



Jan 30, 2020

- "IAA" letters demonstration

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Target relative trajectories

- Hill-Clohessy-Wiltshire (HCW) equations for relative motion dynamics;

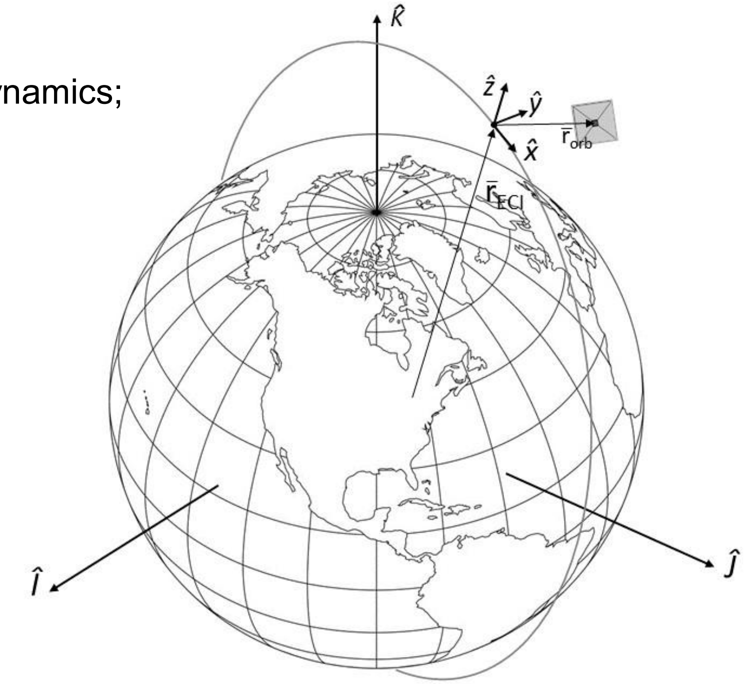
$$\begin{cases} \ddot{x} + 2n\dot{z} = 0; \\ \ddot{y} + n^2 y = 0; \\ \ddot{z} - 2n\dot{x} - 3n^2 z = 0\,. \end{cases}$$

- Analytical solution to HCW equations in case of zero drift and shift along x-axis

$$\begin{cases} x(t) = C_1 \cos(nt + \alpha_0); \\ y(t) = C_2 \sin(nt + \alpha_0); \\ z(t) = \dfrac{C_1}{2} \sin(nt + \alpha_0)\,. \end{cases}$$

- The constants corresponding to the motion of satellite along a circular orbit of radius ***r*** with respect to the orbital reference frame can be defined as follows:

$$C_1 = r$$
$$C_2 = \frac{\sqrt{3}}{2} r$$



Orbital reference frame notation

- X - along track
- Y - normal to the orbital plane
- Z - local vertical

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Impulsive control

- Two-impulse scheme proposed by Vaddi at [3]:

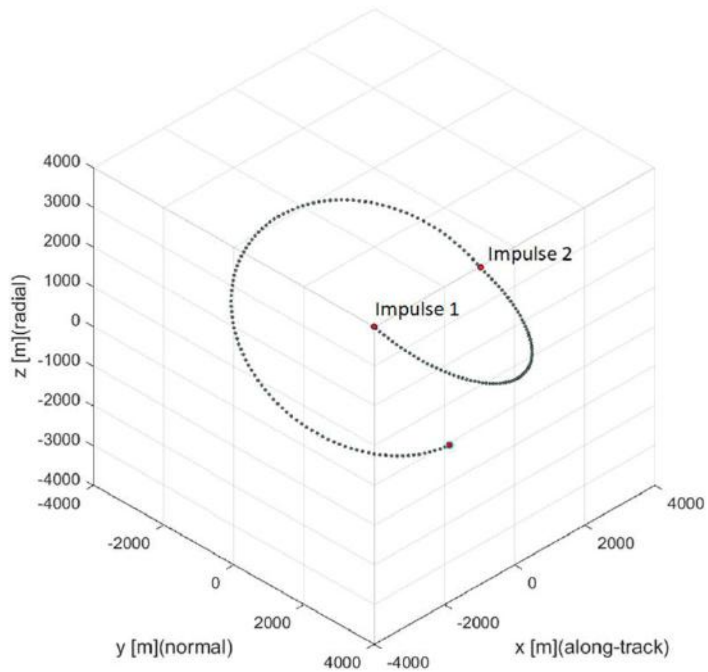
$$dV_1 = \begin{cases} 0 \\ v_{orb}\sqrt{\delta i^2 + \delta\Omega^2 sin^2(i)} \\ -v_{orb}\frac{\sqrt{\delta q_1^2+\delta q_2^2}}{2} \end{cases}; \qquad dV_2 = \begin{cases} 0 \\ 0 \\ v_{orb}\frac{\sqrt{\delta q_1^2+\delta\ {}_2^2}}{2} \end{cases};$$

- Time of thruster firing:

$$t_1 = t_0 + \frac{2\pi - \alpha}{n}; \qquad t_2 = t_0 + \frac{2\pi - \alpha + \pi}{n};$$

where α is the required phase in the circular orbit, n is the mean motion of reference point orbit;

{a, q_1 = e*cos(w), q_2 = e*sin(w), I, Ω, λ} – equinoctial orbital elements

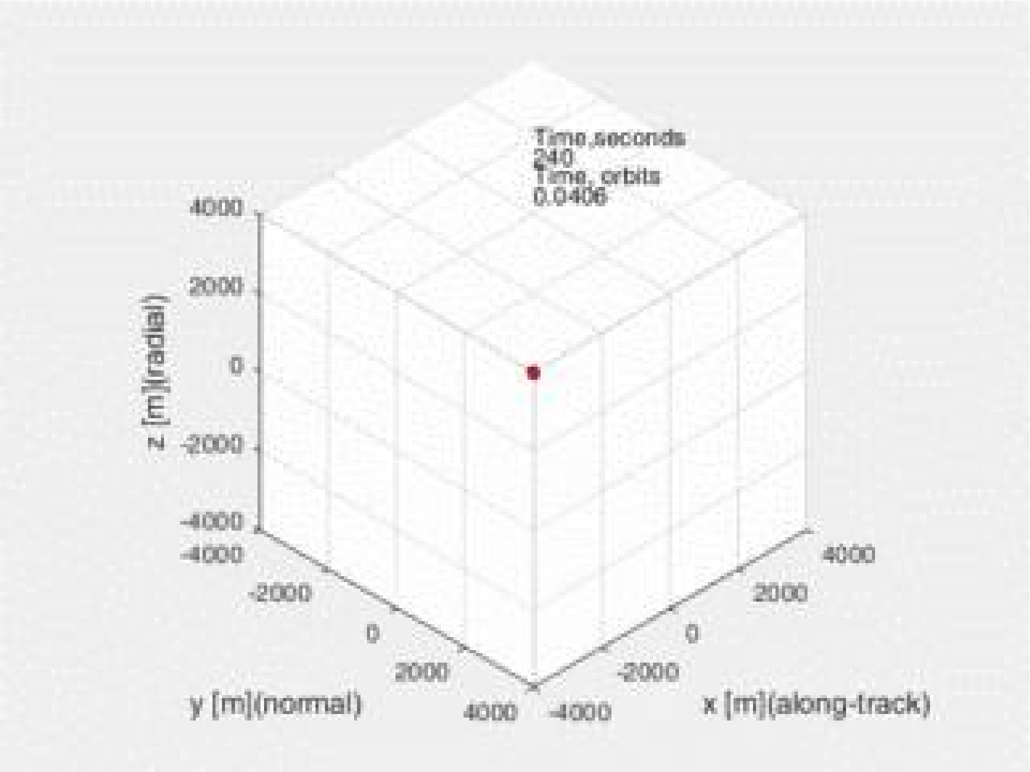


Two-impulse transfer from the origin of orbital reference frame to circular relative orbit of radius 3 km

3. Vaddi, S. S., et al. "Formation establishment and reconfiguration using impulsive control." *Journal of Guidance, Control, and Dynamics* 28.2 (2005): 262-268.

Formation deployment

- Thirty one 12U CubeSats;
- Sunlight reflectors with 11 m^2 area;
- 700 km Sun-synchronous orbit;
- Point of interest – Rome, Italy;
- Minimum angular interpixel distance > 1 arcminute;
- Circular target relative trajectories.



Formation deployment

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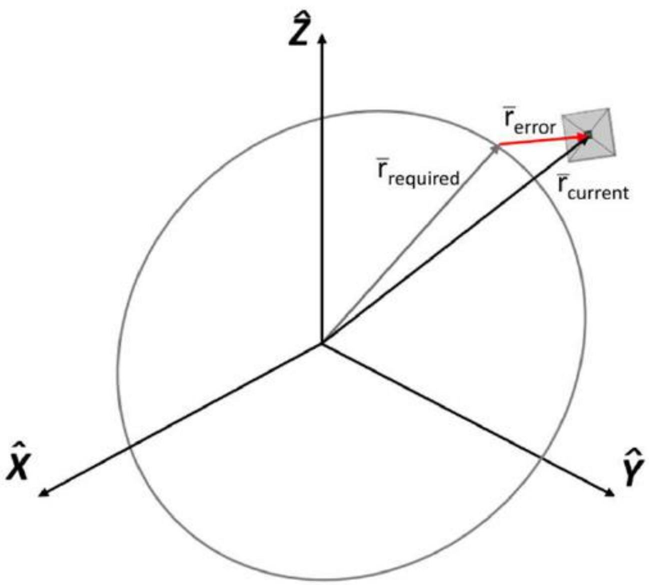
Formation maintenance



Satellite position error

Requirements for corrections with different error thresholds, for 30 days

Acceptable error, %	Time between corrections, hours	Total ΔV, m/s	Propellant mass, g
5	6.8	3	92
10	11.8	2	59
20	23.3	1.4	40

VACCO's Standard Micro Propulsion System as an example of cold-gas thruster, $I_{sp} = 40\ s$

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Conclusion

- Two-impulse control was implemented to **deploy** and **maintain** small satellite formation for graphic image demonstration in the sky;
- Proposed control method has the following advantages: short time of formation deployment and reconfiguration (up to 2 orbit periods), low propellant consumption for formation keeping (up to 100 grams for monthly consumption);
- Since we considered formation deployment and maintenance for orbital dynamics model taking into account only Earth oblateness (J2 effect) we should include in model other disturbances;
- The approach is planned to be applied to reconfigure the geometry of satellite formations to demonstrate a set of different graphic images.

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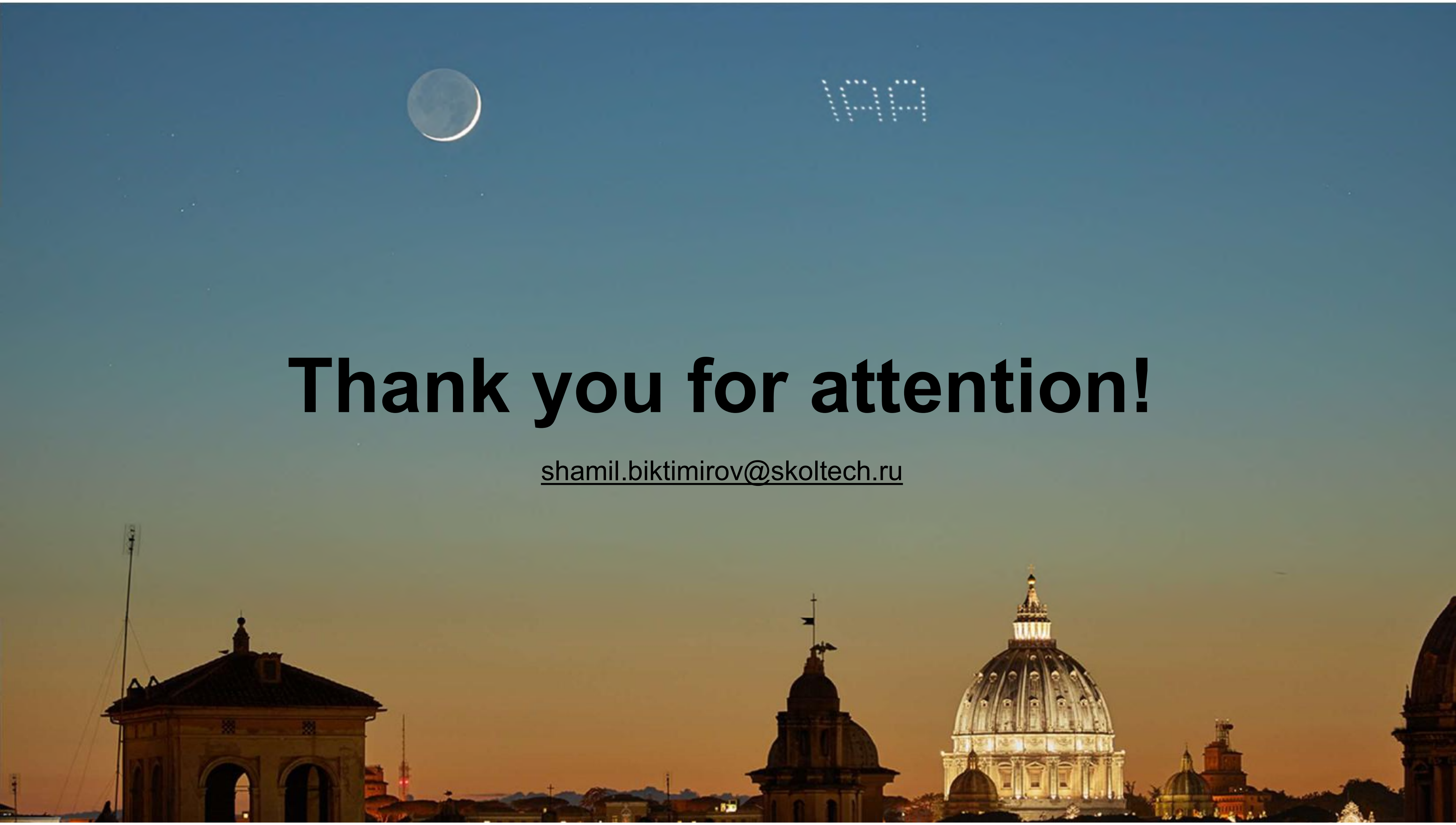

Thank you for attention!

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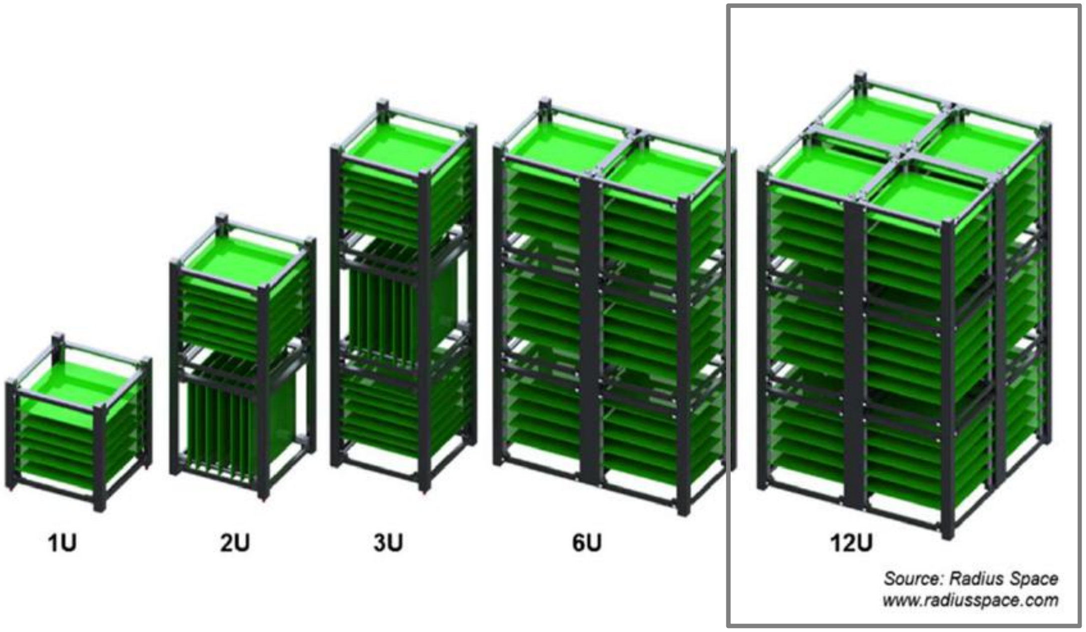
Design Considerations

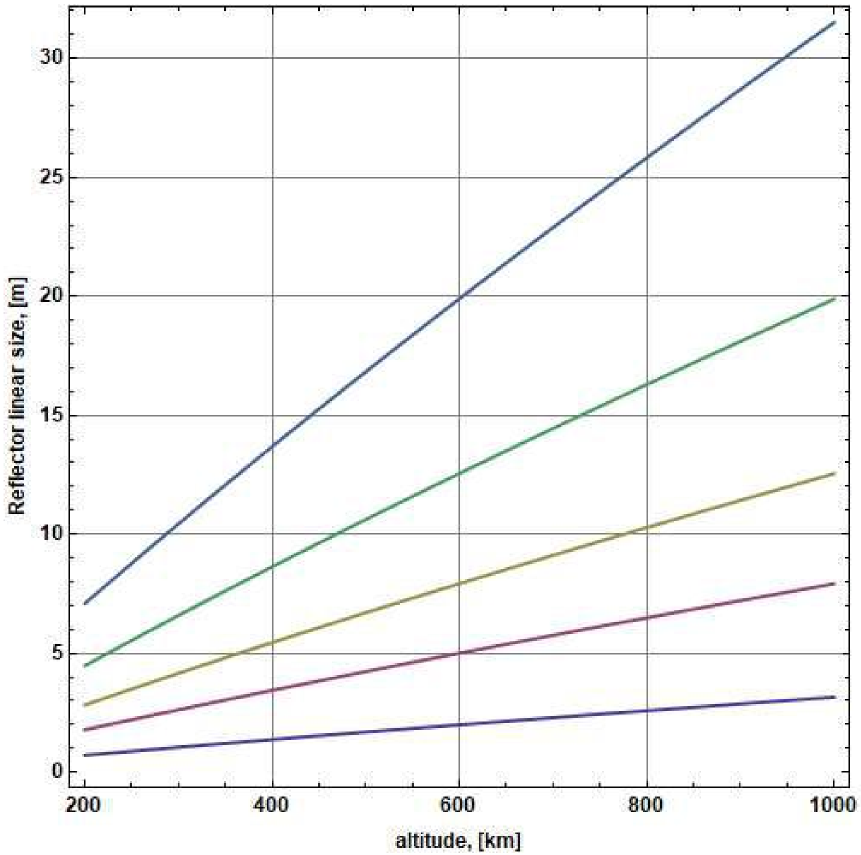


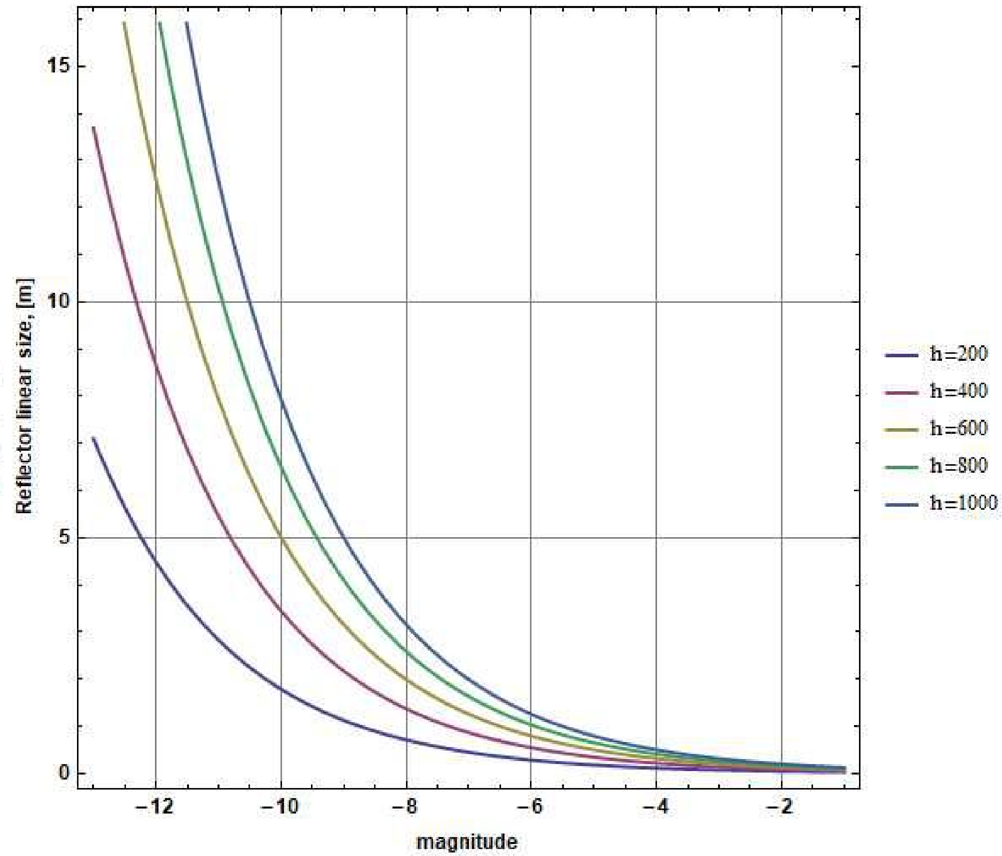
Spacecraft: 12U CubeSat

- 3U – packed reflector
- 3U – thrusters
- 2U – propellant
- 2U – ADCS
- 1U – OBC, telecom
- 1U – batteries

Dimensions: 200 x 200 x 340 mm
Mass: 18 kg
Peak power consumption: ~ 40 W

Payload Size





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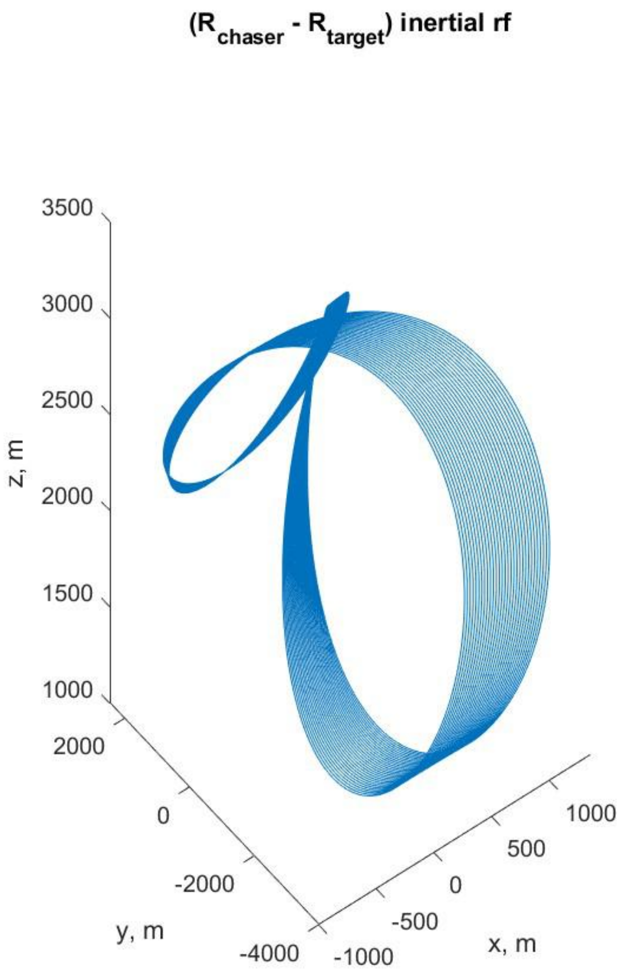
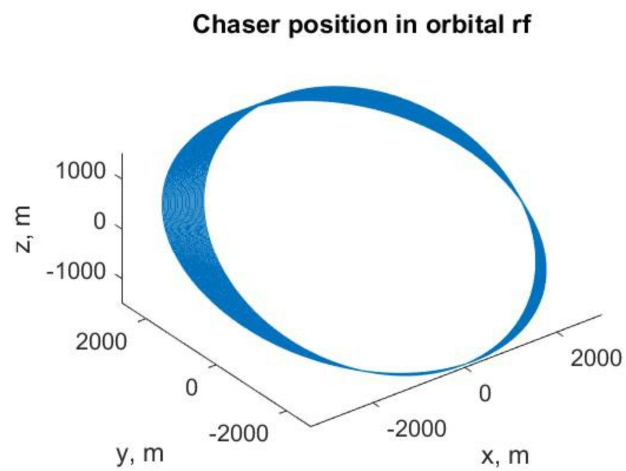
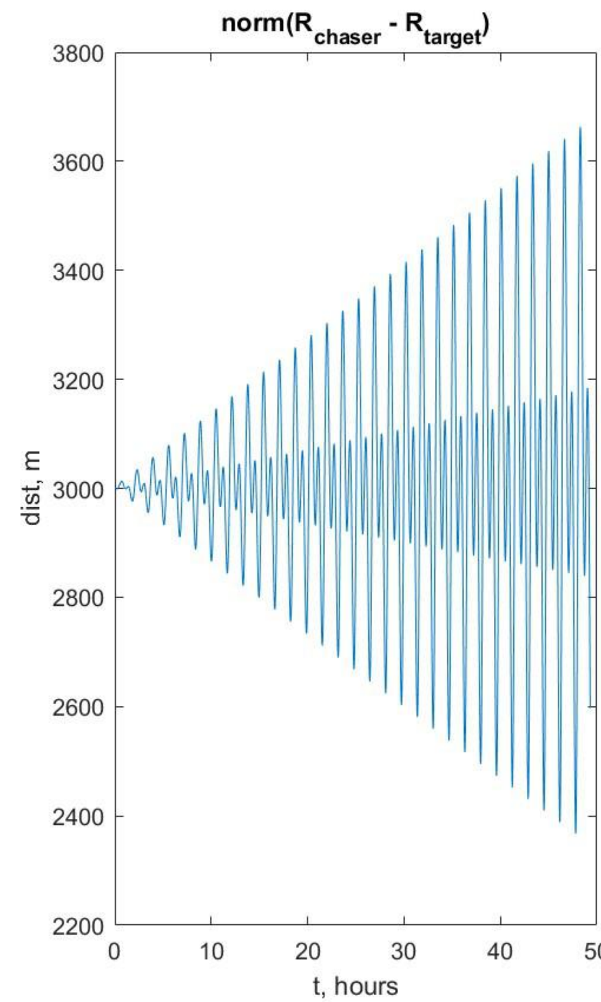

(R chaser - R target) inertial rf
3500
3000
2500
2000
1500
1000
z, m
2000
0
-2000
-4000
y, m
1000
500
0
-500
-1000
x, m


Chaser position in orbital rf
1000
0
-1000
z, m
2000
0
-2000
y, m
2000
0
-2000
x, m


norm(R chaser - R target)
3800
3600
3400
3200
3000
2800
2600
2400
2200
dist, m
0
10
20
30
40
50
t, hours