TETHERED CUBESATS

Arun K. Misra
McGill University
Montreal, Canada

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OUTLINE

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- Fundamentals of Tethered Systems
- Electrodynamic Tethers
- Concluding Remarks

INTRODUCTION

- Tethers have potential for many space applications.
- Tethers can be used for upper atmospheric experiments, electrodynamic propulsion, debris removal, to provide artificial gravity, etc.
- Flight of a large number of tethered systems has already taken place.
- Several of these systems were university-built.
- There is currently greater interests in tethered CubeSats.

TETHERED CUBESAT / NANOSAT MISSIONS

- Probably the most prominent of tethered CubeSat missions is the STARS series of Kagawa University in Japan.

- STARS stands for **S**pace **T**ethered **A**utonomous **R**obotic **S**atellite.

- There have been three so far in this series:
  - STARS-I or KuKai
  - STARS-II
  - STARS-C

STARS-I

- STARS-I or KuKai was launched on 23 January 2009.

- Two satellites named Ku and Kai were linked by a 5 m long tether. The mass of Ku (mother) was 4.35 kg and of Kai (daughter) was 3.61 kg.
- The system was deployed to the planned orbit, but the tether could not be deployed.
- The mission objectives were to test related technologies.

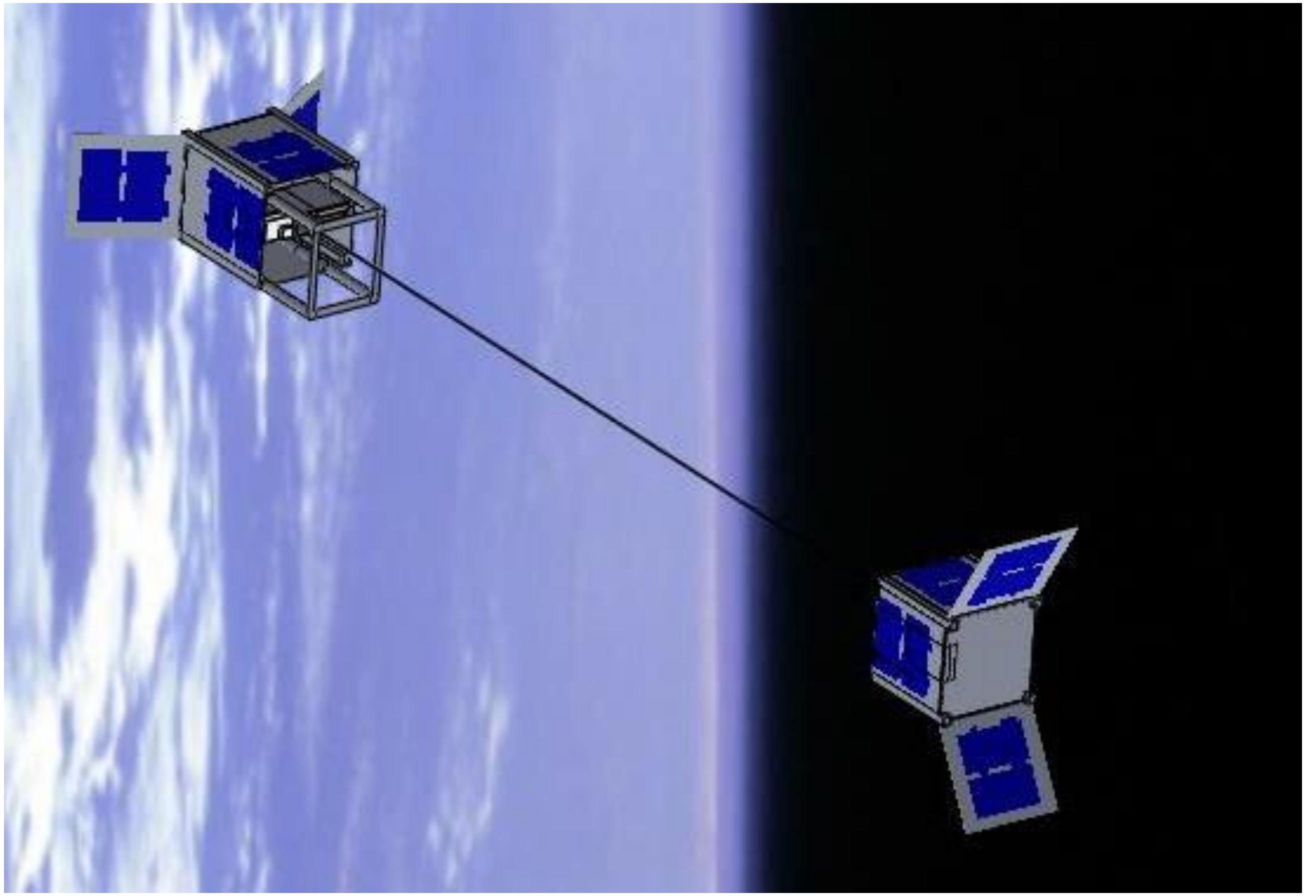
STARS-II

- The follow-up mission STARS-II was launched on 27 February 2014. It deorbited on 26 April 2014.
- The mass of the mother satellite was 5 kg and that of the daughter satellite was 4 kg.
- The satellites were connected by a 300 m electrodynamic tether (EDT).
- Deployment of the tether has not been confirmed. It was not clear from images.
- The orbit decayed faster than other NanoSats; so it is possible that the tether was deployed, at least partially.

STARS-C

- STARS-C was launched from the International Space Station (ISS) on December 19, 2016.
- The system consisted of two 1U CubeSats of total mass 2.66 kg. The tether was made of Kevlar. Its diameter was 0.4 mm and length 100 m.
- Deployment from the ISS was gravity-gradient stabilized.
- Deploying a tethered CubeSats from the ISS has many benefits.

STARS-C



TEPCE

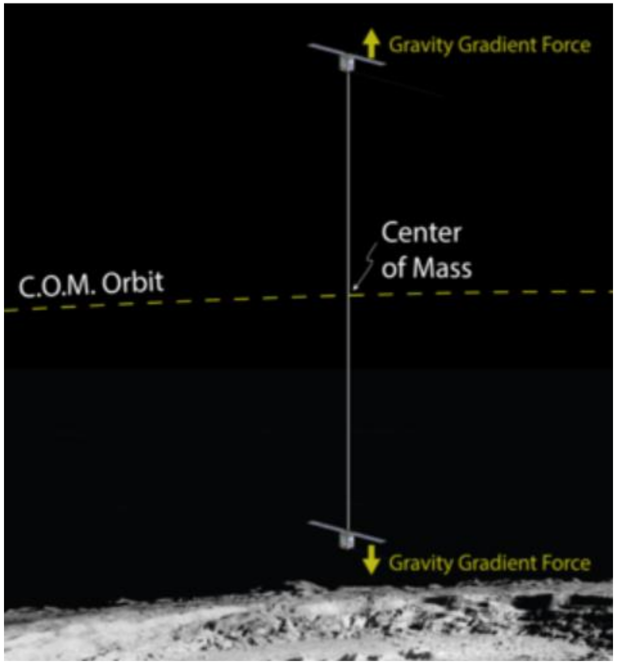
- Tether Electrodynamic Propulsion CubeSat Experiment (TEPCE) is a Naval Research Lab (USA) mission.
- It is an electrodynamic tether (EDT) experiment on a "triple CubeSat" configuration.
- The tether is 1 km long braided type conducting tether.
- Successful deployment test was carried out in May 2010.

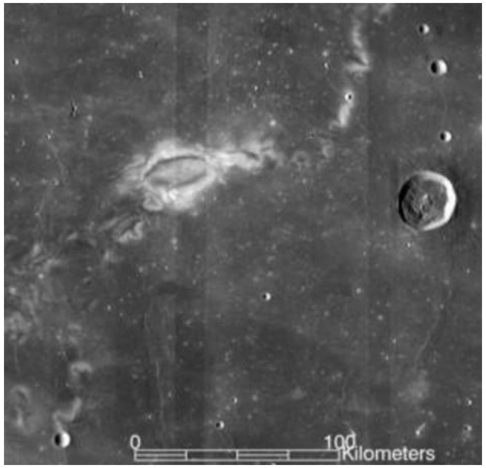
PSDS3

- Planetary Science Deep Space SmallSat Studies (PSDS3) is a NASA Goddard program.
- This is expected to be the first tethered **planetary** CubeSat mission.
- Two 12U CubeSats will be connected by a 112-mile long thin tether.

PSDS3

- The centre of mass of the system will orbit the Moon at 62-mile altitude. The tether will stretch from a height of 6 miles from the lunar surface to 118 miles.
- The orbit will be quasi-stable.
- The system will carry out Bi-sat Observations of the Lunar Atmosphere above Swirls (BOLAS).





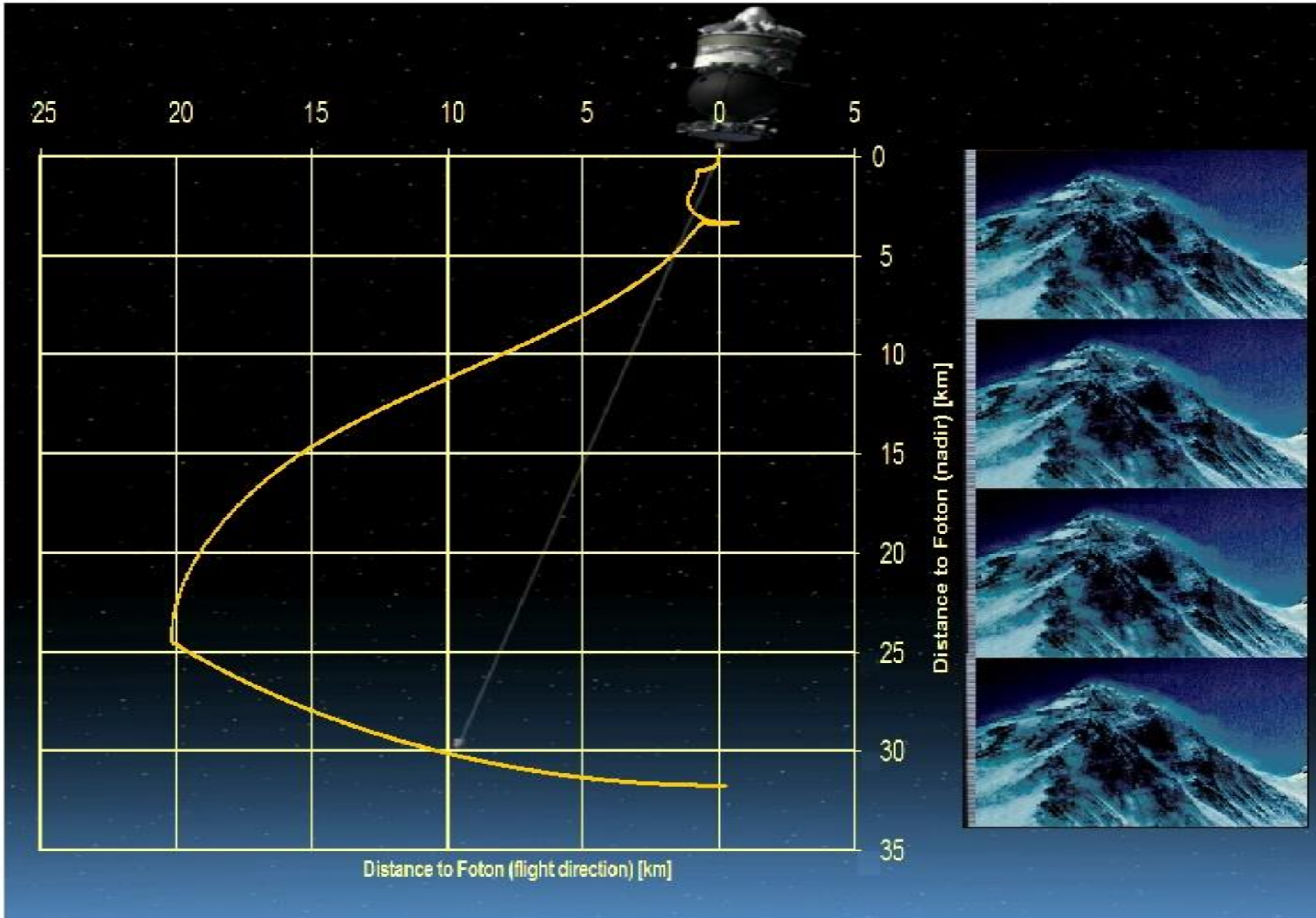
Credit: NASA

MiTEE

- Miniature Tether Electrodynamics Experiment (MiTEE) is a University of Michigan program, supported by NASA.
- A 1U CubeSat is to be deployed from a 3U CubeSat to study electrodynamic tethers (EDT).
- A 10 m **miniature** EDT will be used.

ESTCube-1

- ESTCube-1 was an Estonian mission to test an electric sail in orbit.
- The mission took place in 2013.
- Tether was to be deployed using centrifugal deployment; unfortunately the tether failed to deploy.


25
20
15
10
5
0
5
0
5
10
15
20
25
30
35
Distance to Foton (flight direction) [km]
Distance to Foton (nadir) [km]

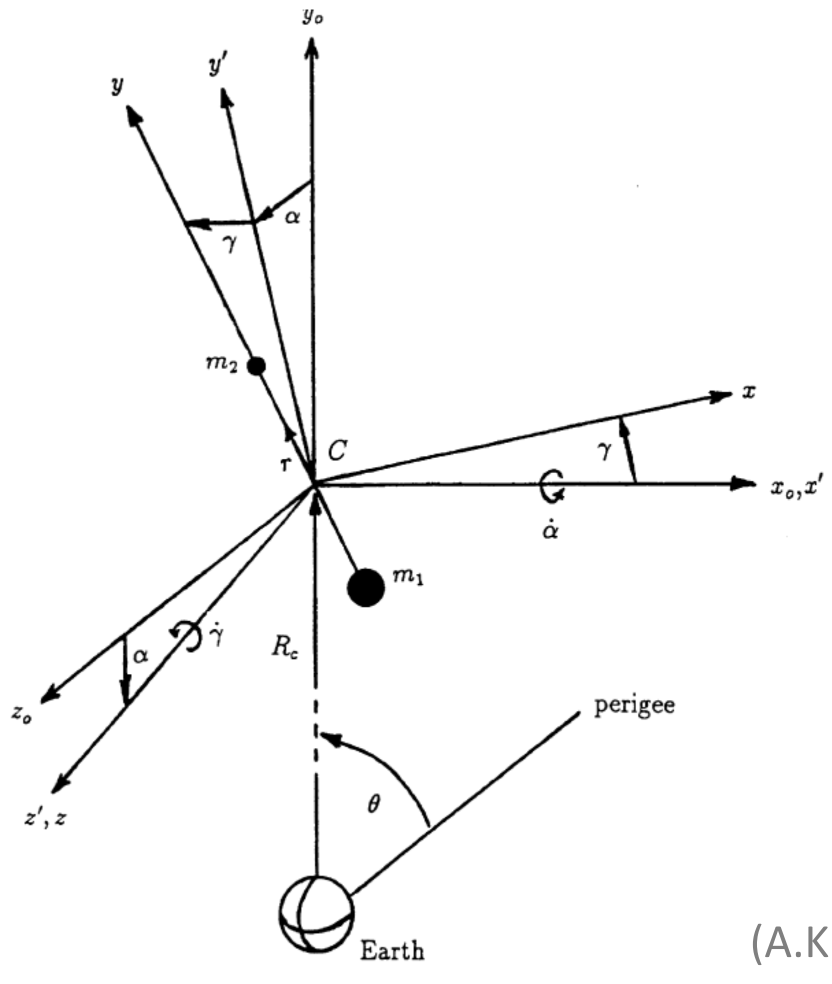
YES2

- Young Engineers' Satellite 2 (YES2) was deployed from Foton-M3 spacecraft on September 25, 2007.
- The tethered satellite Fotino was a 36 kg student-built satellite.
- Fully deployed length was 31.7 km. This is a record for the longest artificial structure in space.
- No signal was ever received from Fotino which was supposed to re-enter earth's atmosphere.
- Four universities were involved:
  - Samara State Aerospace University (Russia)
  - University of Modena and Reggio Emilia (Italy)
  - Hochschule Niederrhein (Germany)
  - University of Patras (Greece)

FUNDAMENTALS OF TETHERED SPACE SYSTEMS

- General dynamics of tethered space systems involves:
  - Pitch and roll motions (librations) of the tether;
  - Longitudinal and transverse oscillations of the tether;
  - Attitude dynamics of the end-bodies;
  - Aerodynamic and electrodynamic forces (if the tether is conducting).
- Pitch and roll motions are only marginally affected by elastic oscillations.
- For many practical situations, librations can be studied by modeling the system as two point masses connected by a straight, rigid tether.

FUNDAMENTALS OF TETHERED SPACE SYSTEMS



(A.K. Misra, 2008)

TETHER FUNDAMENTALS

- Equations governing pitch and roll are (A.K. Misra, 2008)

$$\cos^2\gamma[(\ddot{\alpha}+\ddot{\theta})+\{2r(\dot{\ell}/\ell)-2\dot{\gamma}\tan\gamma\}(\dot{\alpha}+\dot{\theta}) + 3(\mu/R_c^3)\sin\alpha\cos\alpha] = Q_\alpha/m_e\ell^2, \quad (1)$$

$$\ddot{\gamma}+2r(\dot{\ell}/\ell)\dot{\gamma}+[(\dot{\alpha}+\dot{\theta})^2+3(\mu/R_c^3)\cos^2\alpha]\sin\gamma\cos\gamma = Q_\gamma/m_e\ell^2, \quad (2)$$

- m_e and r are given by

$$m_e = [m_1 m_2 + (1/3)m_t(m_1+m_2) + (1/12)m_t^2]/(m_1+m_2+m_t), \quad (3)$$

$$r = [m_1(m_2+(1/2)m_t)]/[m_1 m_2 + (1/3)m_t(m_1+m_2) + (1/12)m_t^2]. \quad (4)$$

- If the tether mass is small, $r = 1$, $m_e = m_1 m_2/(m_1+m_2)$
- The term $\dot{l}$ appears only during deployment. Otherwise, $\dot{l} = 0$.

TETHER FUNDAMENTALS

- For small pitch and roll motions, in the absence of generalized forces and for a circular orbit,

$$\ddot{\alpha} + 3n^2\alpha = 0$$
$$\ddot{\gamma} + 4n^2\gamma = 0$$

- Pitch frequency is $\sqrt{3}$ times the orbital frequency.
- Roll frequency is 2 times the orbital frequency.
- Coupled pitch and roll motions are quasi-periodic in the general case.
- Under certain conditions, motion can become chaotic.

TETHER FUNDAMENTALS

- Tension in the tether arises due to the combined gravity gradient and centrifugal effects.
- Steady state tension is approximately given by

$$T_o = 3m_2\Omega^2\ell_o[1 + (1/2)(m_t/m_2)(1 - s^2/\ell_o^2)]$$

- Clearly, tension can be very small for short tethers.
- The smallest elastic longitudinal frequency varies as $l_0^{-1/2}$, while the others vary as l_0^{-1}.
- The in-plane transverse frequencies are given by

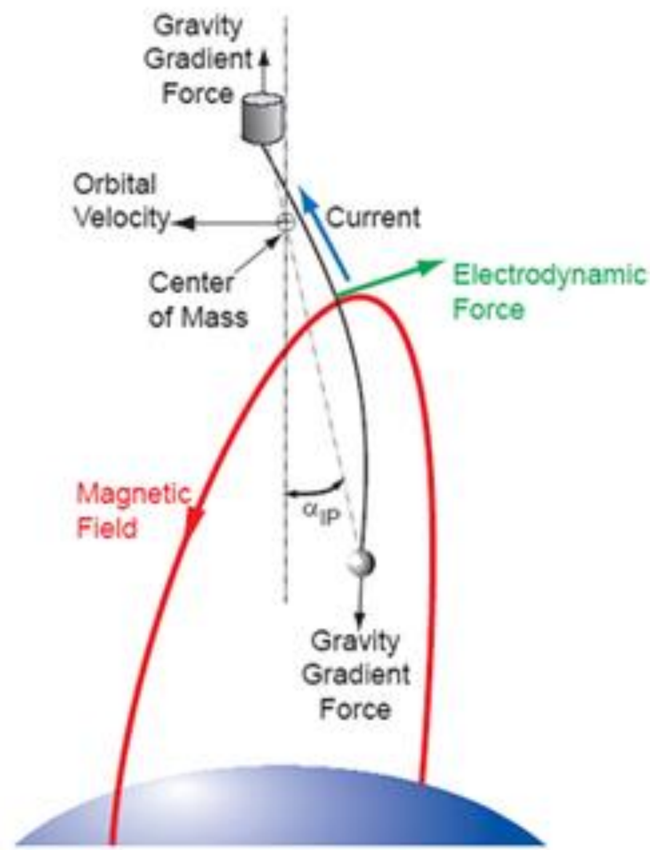
$$\omega_{n_I} = \beta_n(3m_2/m_t)^{1/2}\Omega, \quad \beta_n^2 = n^2\pi^2[1 + (m_t/3m_2)] - (m_t/4m_2)$$

- The out-of-plane transverse frequencies are given by

$$\omega_{n_o}^2 = \omega_{n_I}^2 + \Omega^2$$

ELECTRODYNAMIC TETHERS

- Motion of a conductive wire across the magnetic field of the Earth induces an emf and Lorentz force.
- This “electrodynamic propulsion” can be used to raise or change the orbit.
- This effect can be utilized for removal of space debris.



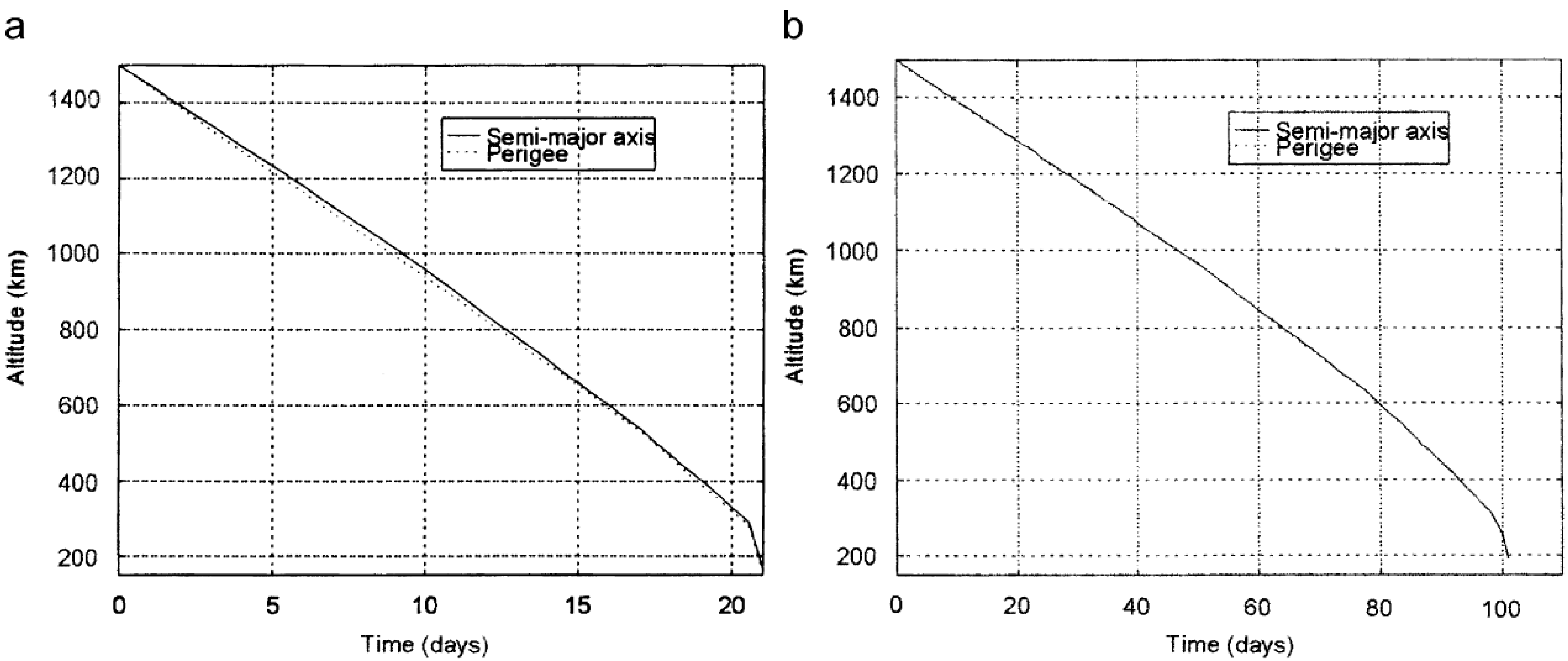


Fig. 7. Orbital decay for circular orbit at 1500 km; (a) $i = 0^\circ$ and (b) $i = 85^\circ$ (Ref. [13]).

[13] E.L.M. Lanoix, A.K. Misra, V.J. Modi, G. Tyc, Effect of electromagnetic forces on orbital dynamics of tethered satellites, in: AAS/AIAA Spaceflight Mechanics Meeting, Clearwater, Florida, Paper No. AAS-00-189, 2000.

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CONCLUDING REMARKS

- Many tether experiments that were being conducted using larger satellites, can be conducted using CubeSats.

- The majority of tethered CubeSat missions are university-centered, although there is also interest from government agencies.