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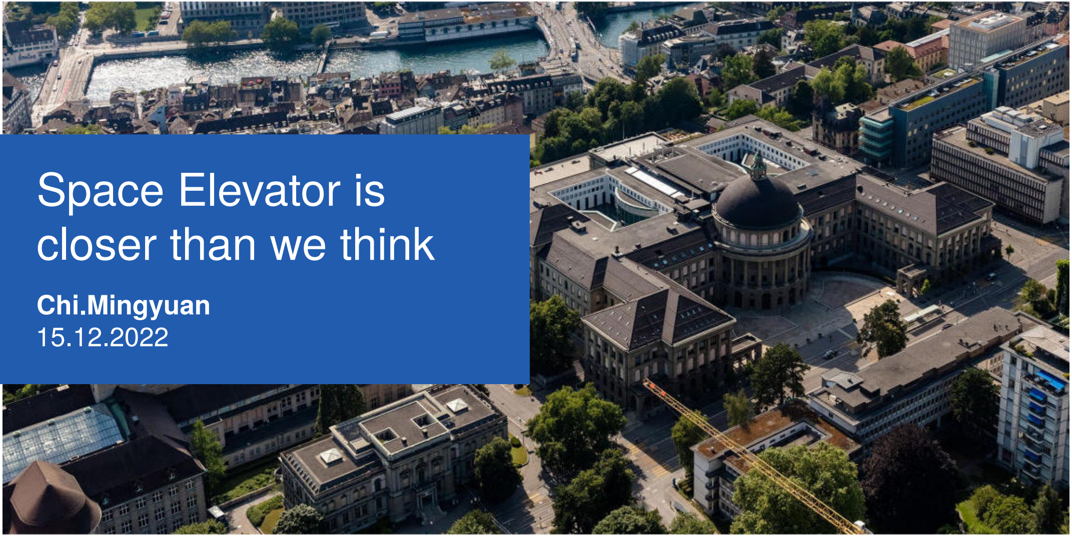
Department of Mathematics



Space Elevator is closer than we think

Chi.Mingyuan

15.12.2022

Humanity either spreads across the universe or perishes completely. No other choice.

–Liu.Cixin(H.G.Wells)

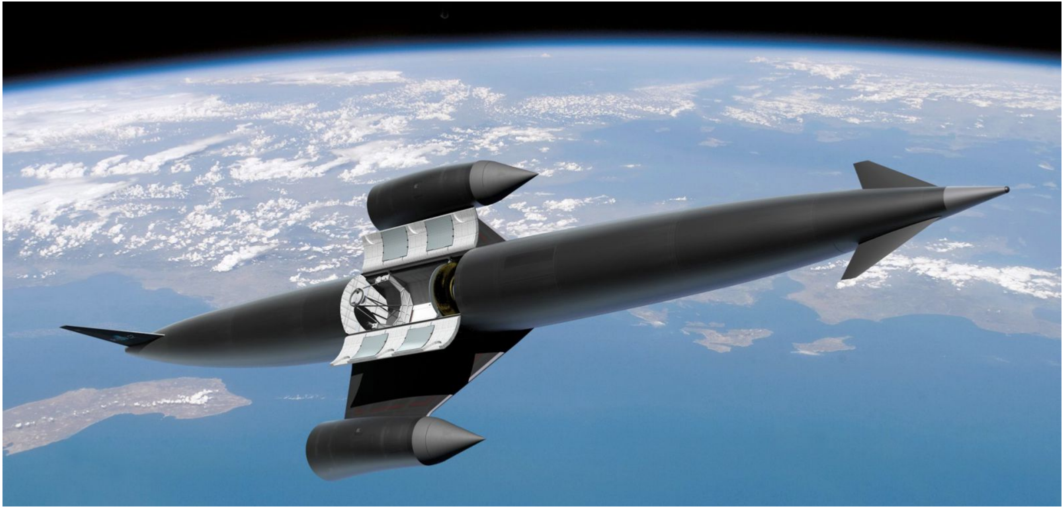
Outline

1. Background
2. Introduction
3. Cable
4. Initial Cable Deployer
5. Climber
6. Power
7. Challenges
8. Modern Space Elevator Design

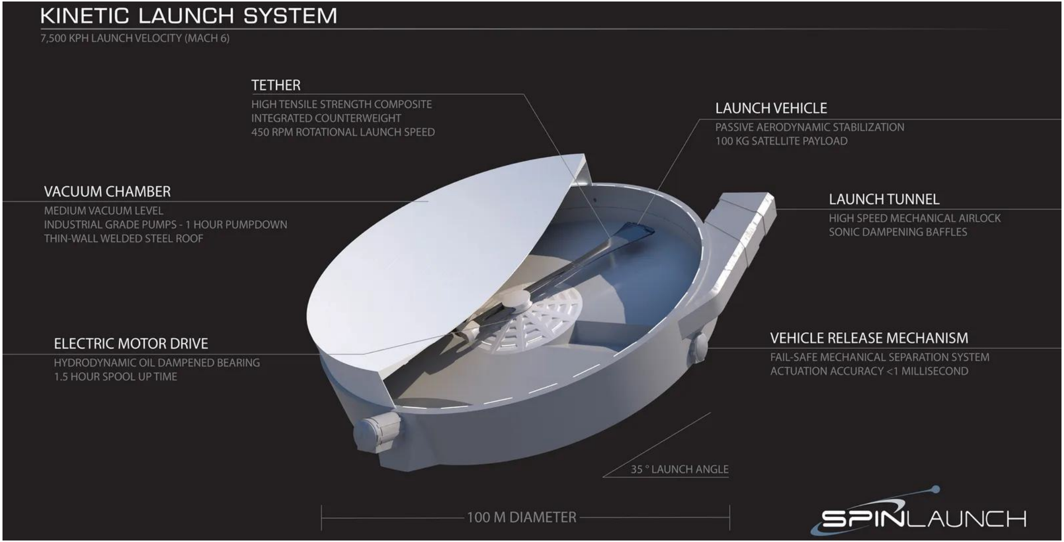
Outline

Rocket
StarShip(SpaceX)

Space Airplane
Skylon(Reaction)

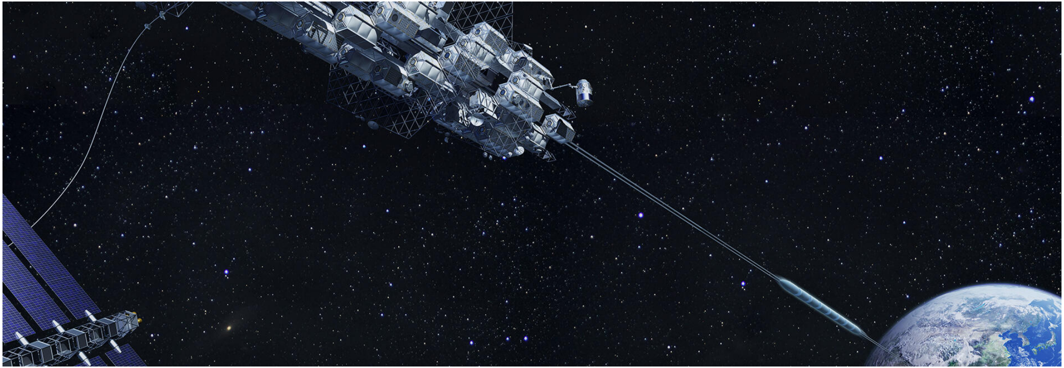


Mass Driver
MassAccelerator(SpinLaunch)



Space Elevator

SpaceElevator(Obayashi)



Outline

Introduction

NASA Institute for Advanced Concepts (NIAC) program [1] [2]

1. Deploy a minimal cable $1\mu m \times (5cm \sim 11.5cm) \times 91000km$

   1238 kg

2. Increase this minimal cable to a useful capability

   1.5% stronger each.

   207climbers(2.3 years) 20,000kg climber 13,000 kg payload.

   2.3 + 2.8 years 1000,000kg.

   shuttle orbiter.

3. Utilize the cable for accessing space

   space solar power station, asteroid mining, colonize other planets...

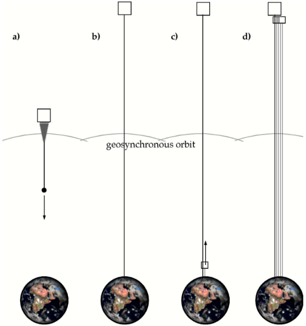


Fig 1.3: Illustration of the deployment scenario for the space elevator. A) A spacecraft is sent to geosynchronous orbit where it begins deploying a small cable. As the cable is deployed the spacecraft floats outward. B) When the end of the cable reaches Earth it is retrieved and anchored. C) Climbers are sent up the initial cable to strengthen it. D) A usable, high-capacity cable is completed.

Outline

Cable
micro-scale

section drawing
Carbon Nanotube (50cm in 2013 [3])

CNT(60%)-epoxy(40%) compound

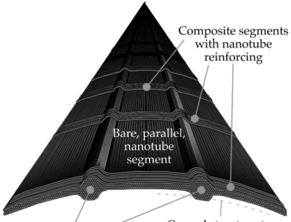


Fig. 2.5: Cut-away view of the proposed ribbon cable.

Edward's Design

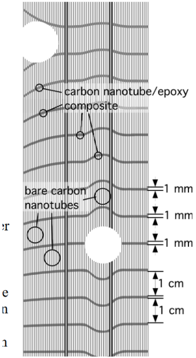


Fig. 2.4: Basic design of cable (5 cm width) with meteor damage.

Hoyt's Design

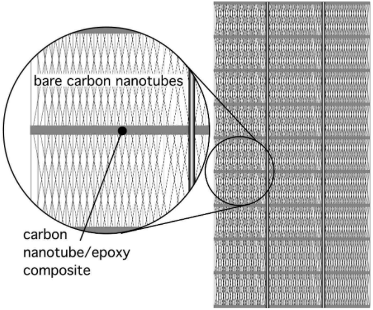


Fig. 2.7: A possible cable design based on the Hoytether. This version has all the fibers under tension (well below breaking), composite strips to connect the nanotubes and isolate the cable segments and two thicker reinforcing fibers.

Cable
macro-scale

- $< 7km(2cm \times 5\mu m)$
- $7km \sim 500km(10cm \times 1\mu m)$
- $500km \sim 1700km(wider)$
- $> 1700km(10cm \times 1\mu m)$

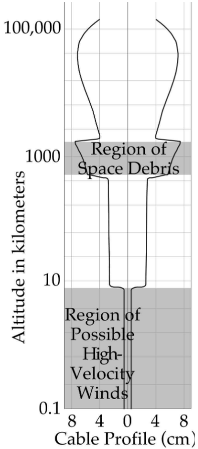


Fig. 2.3: The width profile of the proposed cable.

Cable
production

Element: only short CNT needed [4]

Strength: no defects cable are allowed

Speed: each cable in one year, 100 in parallel

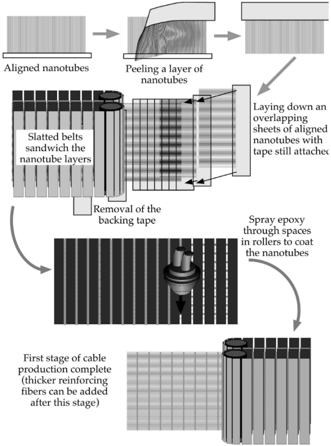


Fig. 2.8: One possible production scenario. The time consuming part of this and probably any production scheme is the epoxy curing.

Outline

Initial Cable Deployer
deployer

Weight: about 20 ton!(Falcon Heavy(GEO) 27 ton)

168,000kg (19,800kg cable) GEO.(ISS 420,000kg, TSS 180,000kg)

Power: no extra power is required to deploy the cable.

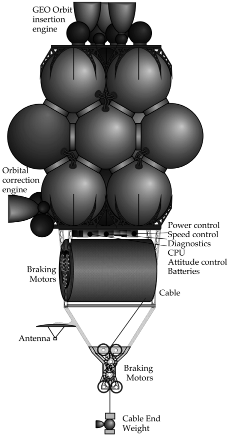


Fig. 3.1: Basic schematic of spacecraft to deploy the initial cable. Approximately to scale with each propellant tank about 2.6 meters (8 ft) in diameter.

Initial Cable Deployer
deploy

- **Angular Momentum**:impart small angular moments

- **Ground Detection**: transmit beacon signal, end of the cable can be found on the earth.

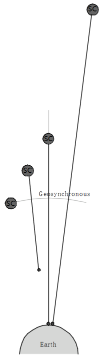


Fig. 3.2:Deployment of the initial cable. The cable is deployed downward (see discussion on imparting angular momentum to the cable) as the spacecraft is held in a geosynchronous orbit.

Outline

Climber
deploy

Weight: first climber total mass: 619kg(288kg cable)

Usage: first widen then thicken the cable.

first widen 30cm at 200km/h. then thicken.

Expandable: expandable design as it become larger each climb.

Defect: low altitude retrieve, high altitude release.

Power: The higher power the faster the deploy and more robust.

power-kilogram ratio > 40%(113W/kg). 20,000kg in 1.7 years, 1000,000kg in 3.7years. reduce cable damage(47.84 kw/kg in 2022)

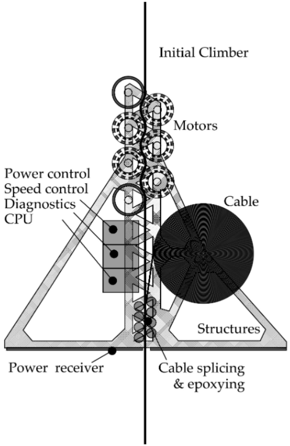


Fig. 3.3: Illustration of the various components of a climber.

Outline

Power
deploy

	Laser	Microwave
Operation wavelength	$0.84\mu m$	$3.2mm$
Transmitter System	free-electron laser deformable mirror	phased array
Transmitter Area	12m diameter	1km diameter
Receiver System	Solar Cells	Rectennas
Overall Efficiency	2%	0.05%

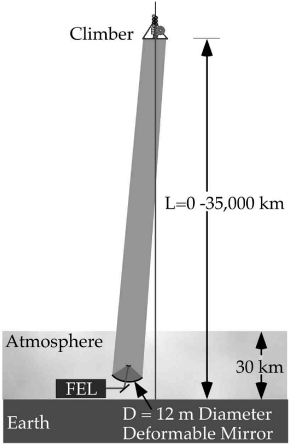


Fig. 4.1: Illustration of the laser beaming scenario.

Outline

Challenges
Lightning

no good method to protect.
lightning-free zone

lightning rod, laser

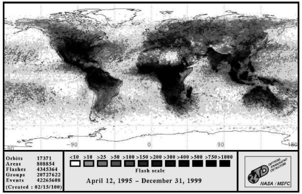


Fig. 10.1.2: Global map of lightning strikes [Christian, 1999] (flashes/km²/year) showing regions of high activity (central land masses)and regions of low activity (eastern Pacific, northern Africa, and mountain ranges including the Andes and the Himalayas).

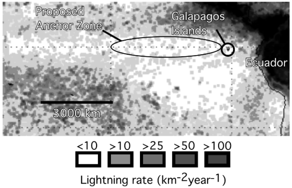


Fig. 10.1.3: Expanded view of the "lightning-free" zone in the Pacific Ocean.

Challenges
Meteors&Space Debirs&Low-Earch-Orbit

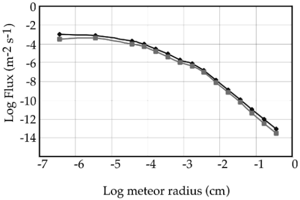


Fig. 10.2.1: Micrometeor data from Staubach, 1997. This data agrees well with that of Manning, 1959 which was used in the space elevator paper by Edwards, 2000.

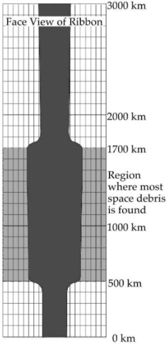


Fig. 10.3.1: Sketch of how the width of the cable may be modified to improve its survivability in regions where space debris is most prevalent.

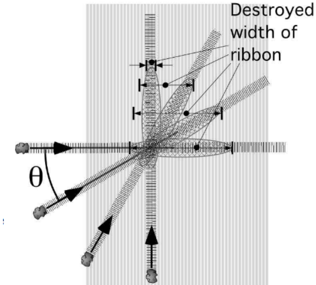


Fig. 10.2.3: Dependence of impact damage on angle of impact relative to long axis of cable. The destroyed width of ribbon cable is the critical parameter.

Challenges
Wind

wind-free zone
special design

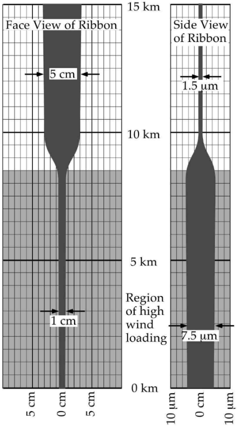


Fig. 10.4.2: Modified cable design to deal with wind loading. Note: In the right hand profile the dimensions are for the average thickness across the ribbon.

Challenges
Atomic Oxygen

the most tricky challenge
coat with $Ni + SiO_2$ as thin as
0.16 μm or Pt and Au

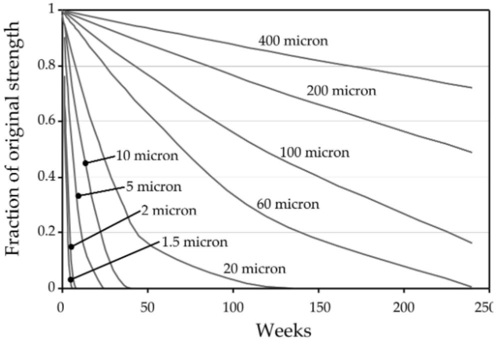


Fig. 10.5.1:Degradation by atomic oxygen of different diameter carbon/epoxy composite fibers as a function

Challenges
Others

Challenges	Solution
Electromagnetic fields	radiate into the space
Radiation	maintain more than 1000 years
Oscillation	characteristic period 7.1 hours. climber no more than 10,000km/h
Environment Impact	Reentry will burn the cable

Outline

Modern Space Elevator Design
Cable

Graphene

similar mechanics performance as CNT, but much easier to produce in large scale [5].

or even diamond nanothread(50nm in 2015)

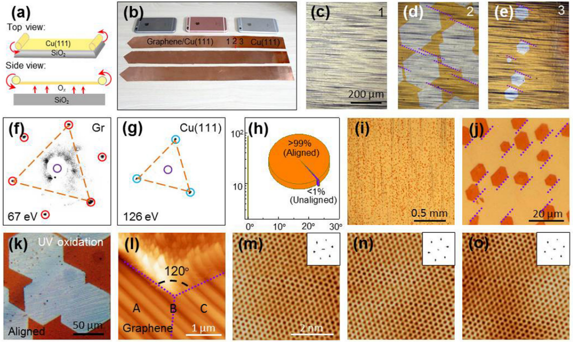
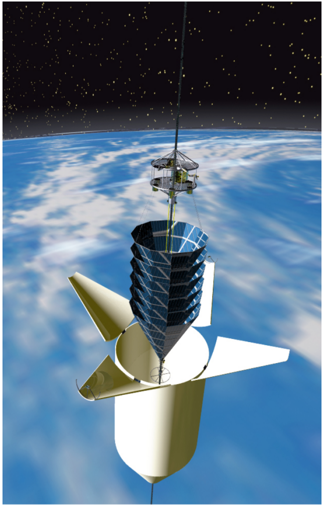


Fig. 3. (Color online) Continuous growth of (5 × 50) cm^2 graphene films on the surface of the annealed single-crystal Cu(1 1 1) foil. (a) Top and side schematic views of the continuous graphene film growth system, where the Cu(1 1 1) foil was placed above a SiO_2 substrate with a small separation, for ultrafast growth. (b) Cu(1 1 1) foils with graphene coverages of ~60% (top), ~90% (middle) and 100% (bottom), where the "shining" parts are graphene/Cu (left side). The three iphone 6s are placed nearby as a reference. (c–e) Optical images of three regions of the graphene covered Cu(1 1 1) foil (marked as 1, 2, 3 in (b)) where graphene fully covered the Cu foil (c), areas with aligned large graphene islands (d) and aligned small graphene islands (e) are clearly seen on the left of, on the right of, and at the growth front, respectively. (f-g) The LEED patterns of as-grown graphene film (f) and the underlying Cu substrate (g) show that graphene islands grew epitaxially on the Cu(1 1 1) surface. (h) The orientation angle distribution of the measured 1200 LEED patterns of the graphene film, showing that all of them are aligned. The inset: percentage of the aligned graphene islands measured from optical images (Fig. S5, online). (i-j) Optical image of the randomly distributed holes formed by H_2 etching of the graphene film. Edges of the holes marked by the dashed lines are parallel with each other. (k) Optical images of aligned graphene islands after UV oxidization for 10 min. (l) A large-scale STM image near the corner of two merged aligned graphene islands. (m–o) Representative atomic-resolution STM images corresponding to the A, B, and C regions marked in (l), showing that there are no defects formed during the island coalescence. Insets: fast Fourier transformation patterns of the STM images.

Modern Space Elevator Design
Climber

Solar Power above the atmosphere



[1] Bradley C Edwards. "Design and deployment of a space elevator". In: *Acta Astronautica* 47.10 (2000), pp. 735–744.

[2] Bradley C Edwards and Eric A Westling. *The space elevator*. BC Edwards, 2003.

[3] Rufan Zhang, Yingying Zhang, Qiang Zhang, et al. "Growth of half-meter long carbon nanotubes based on Schulz–Flory distribution". In: *Acs Nano* 7.7 (2013), pp. 6156–6161.

[4] F Li, HM Cheng, S Bai, et al. "Tensile strength of single-walled carbon nanotubes directly measured from their macroscopic ropes". In: *Applied physics letters* 77.20 (2000), pp. 3161–3163.

[5] Xiaozhi Xu, Zhihong Zhang, Jichen Dong, et al. "Ultrafast epitaxial growth of metre-sized single-crystal graphene on industrial Cu foil". In: *Science bulletin* 62.15 (2017), pp. 1074–1080.

Thank you

Chi.Mingyuan
minchi@student.ethz.ch

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Deployment

- MMH : monomethylhydrazine
- NTO : nitrogen tetroxide
- SC : space craft

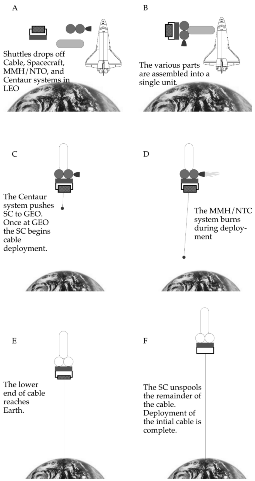

Fig. 5.2:Deployment scenario for the initial cable.

Anchor

- equator
- lightning-free zone
- avoid from hurricane

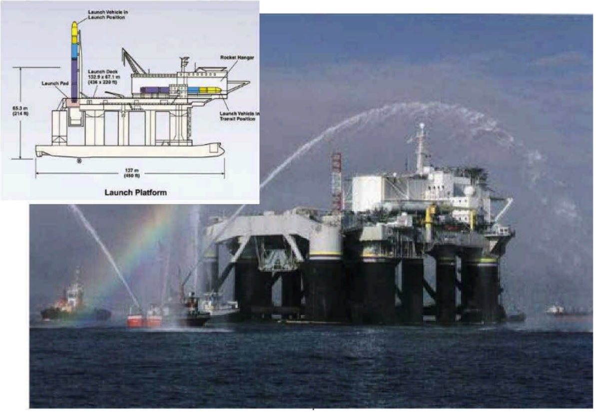

Fig. 6.1: Odyssey from the Sea Launch program.

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Destination

The speed increment from earth to earth orbit is more than that from earth orbit to escape the solar system.(The gravity is the prison)

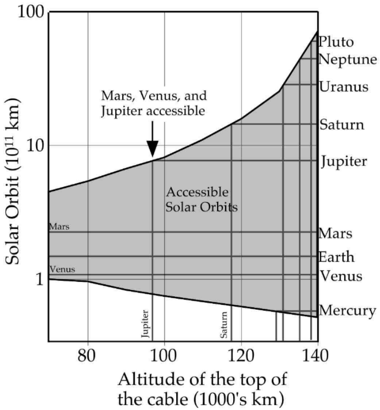

Fig. 7.1: Accessible solar orbits from the space elevator. The orbits of the planets are marked along with the cable required to access each.

Advantage

- 99% reduction in cost
- less space debris
- repair and removal spacecrafts
- large-scale commercial manufacturing in microgavity space
- large-orbit solar collectors for power generation
- ...

Termionlogy

- **LEO**:Lowest Earth Orbit
  where the period of 128min or less

$$r_{LEO} \approx 200km + R_{earth}$$

- **GEO**:Geostationary Equatorial Obit
  only in equator and following the direction of Earth's rotation.

$$\begin{aligned} r_{GEO} &= \sqrt[3]{\frac{GMT^2}{4\pi^2}} \\ &\approx 42164km \\ &\approx 35786km + R_{earth} \end{aligned}$$

Annotation
Space Elevator height and tape ratio

Notation

- r_0 : earth radius
- g_0 : surface gravity
- r_s : synchronous orbit radius
- ρ : density of the cable
- A : cross-sectional area
- A_s : cross-sectional area at synchronous orbit radius
- r_t : the end of the cable
- σ : uniform stress
- h : characteristic height $h = \frac{\sigma}{\rho g_0}$

The total gravity force should equal to the centrifugal force

$$F = \int_{r_0}^{r_t} \rho A g_0 r_0^2 (1/r^2 - r/r_s^3) dr = 0$$

$$\Rightarrow r_t \approx 150,000km$$

assuming the stress in the cable distributed uniformly.

$$\sigma dA = \rho g_0 r_0^2 (1/r^2 - r/r_s^3) A(r) dr$$

$$\Rightarrow A(r) = A_s e^{3r_0^2/2hr_s} e^{(-r_0/h)(r_0)}$$

$$\Rightarrow \frac{A_s}{A_0} = e^{0.776 r_0/h}$$

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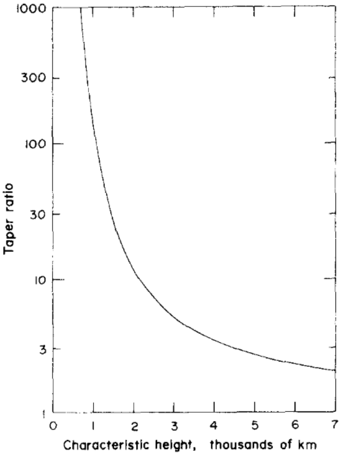
Annotation
Space Elevator height and tape ratio



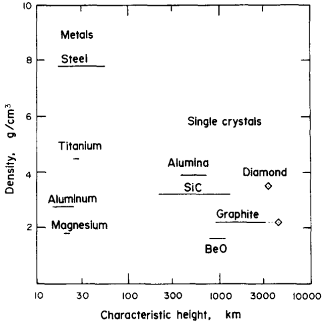


Fig. 2. Characteristic height vs density for various materials.

Deploy Speed

Notation

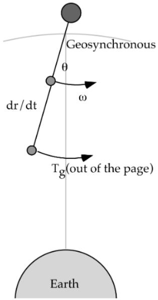
- T_g : gravitational torque
- R : orbit radius
- μ : earth gravity constant $(3.9 \times 10^5 km^3/s^2)$
- θ : maximum deviation of Z axis from the vertical
- ω : angular velocity of the earth $(7.3 \times 10^{-5} s^{-1})$
- I : angular momentum of the spacecraft (mr^2)
- m : weight of the cable end

$$T_g = \frac{3\mu}{R^3}|I_z - I_y|\theta$$

$$T_g = \frac{d(I\omega)}{dt} = \omega m r \frac{dr}{dt}$$

$$\Rightarrow \frac{3\mu}{R^3} m r^2 \theta = \omega m r \frac{dr}{dt}$$

$$\Rightarrow r = e^{\frac{3\mu\theta}{\omega R} t}$$



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Angular Momentum

The climber gain horizontal speed(angular momentum) from the rotation of the earth(Corioils Force).