Lowering Launch Costs to Facilitate Human Space Exploration

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Human presence in space

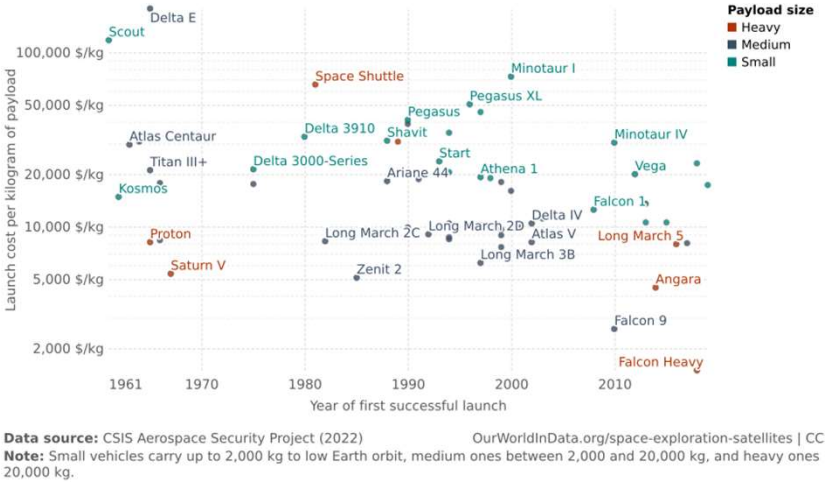
- “Domiciled on a planet, living space will not be a major problem for [Type I] cultures. But emergent Type II societies will find no such ready-made living quarters in orbit.” (Freitas)

Expansion of Human presence in space is necessary for the advancement of our species.

- Limited area on Earth
- Growing population and industry
- Resources in space

Current technology

- Improvements over time
  - Better launch systems
  - Better technology
  - Economies of scale



Data source: CSIS Aerospace Security Project (2022) OurWorldInData.org/space-exploration-satellites | CC
Note: Small vehicles carry up to 2,000 kg to low Earth orbit, medium ones between 2,000 and 20,000 kg, and heavy ones 20,000 kg.

- TRL9 now: SpaceX Falcon Heavy
  - $1500/kg
- Cost still prohibitive for space habitation

By SpaceX - Falcon Heavy Demo Mission, CC0, https://commons.wikimedia.org/w/index.php?curid=66389585

Current technology

Cost of going to space

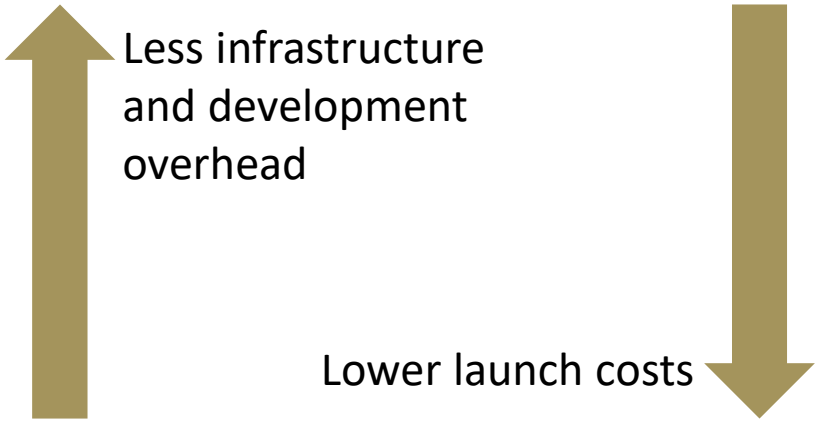
	1 million people	1 billion people
Cost/kg	$1,500	$1,500
Development cost	(completed)	(completed)
kg material needed	~50 B	~50 T
Launch cost	$75 Trillion	$75 Quadrillion
Construction cost	(completed)	(completed)
Development cost	(completed)	(completed)
Total cost	$75 Trillion	$75 Quadrillion
~	9 mo. World GDP	15x world value

Verdict: Not possible.

By SpaceX - Falcon Heavy Demo Mission, CC0, https://commons.wikimedia.org/w/index.php?curid=66389585

We need better launch systems

- Current launch systems cannot get humanity to space at scale
- New launch systems are needed.
- Potential Concepts
- More infrastructure and development needed for lower costs
  - Ultra-heavy launch vehicles
  - Space cannons
  - Skyhooks
  - Rotovators
  - Launch loops
  - Space elevator
  - Orbital ring



Ultra-heavy launch

- Improvements over time (**AMPLIFIED**)
  - **Better launch systems**
  - **Better technology**
  - **Economies of scale**
- What we are already doing, but **MORE!**
- Development: In Progress
- Multiple Designs
  - Sea Dragon
  - Space Launch System
  - Starship
- Most likely candidate: SpaceX Starship
  - $667/kg?
  - More improvement certain to be made
- Sea Dragon
  - $500/kg

SPACEX

https://www.reddit.com/r/SpaceXMasterrace/comments/oe12tx/sea_dragon_sls_starship_superheavy_new_shepard/

Ultra-heavy launch

- Improvements over time (**AMPLIFIED**)
  - **Better launch systems**
  - **Better technology**
  - **Economies of scale**
- What we are already doing, but **MORE!**
- Development: In Progress
- Multiple Designs
  - Sea Dragon
  - Space Launch System
  - Starship
- Most likely candidate: SpaceX Starship
  - **$667/kg?**
  - More improvement certain to be made
  - **$333/kg?**

SPACEX

https://www.reddit.com/r/SpaceXMasterrace/comments/oe12tx/sea_dragon_sls_starship_superheavy_new_shepard/

Ultra-heavy launch

Cost of going to space

	1 million people	1 billion people
Cost/kg	$333	$333
Development cost	$Billions	$Billions
kg material needed	~50 B	~50 T
Launch cost	$16.65 Trillion	$16.65 Quadrillion
Construction cost	$100 Million	$100 Million
Development cost	$Billions	$Billions
Total cost	$16.653 Trillion	$16.65 Quadrillion
~	33 mo. US gov.	3x world value

Verdict: Not possible?

SPACEX

https://www.reddit.com/r/SpaceXMasterrace/comments/oe12tx/sea_dragon_sls_starship_superheavy_new_shepard/

Space cannons

- Actual infrastructure
  - Short-circuiting current improvement trends
- Escapes the tyranny of the rocket equation!
- Development in the 20th century by
  - Nazi Germany
  - Ba'athist Iraq
- Only works for payloads with high g-tolerance
  - $220/kg (Green Launch - $100/lb) for 95% of the payload
  - $1500/kg for the remaining 5% since it must be launched normally.
  - Avg. $284/kg

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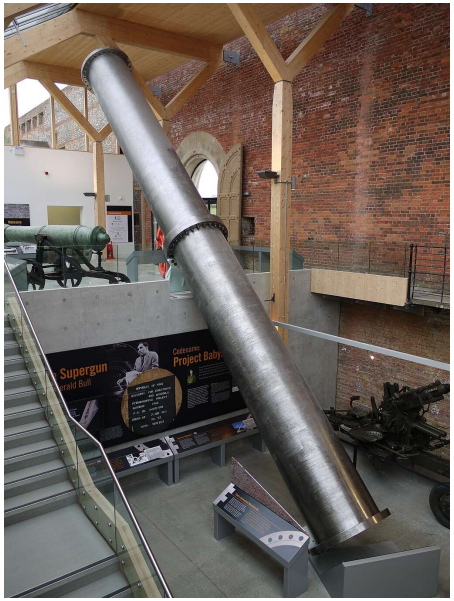

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Jules Verne, From The Earth To The Moon

GREENLAUNCH

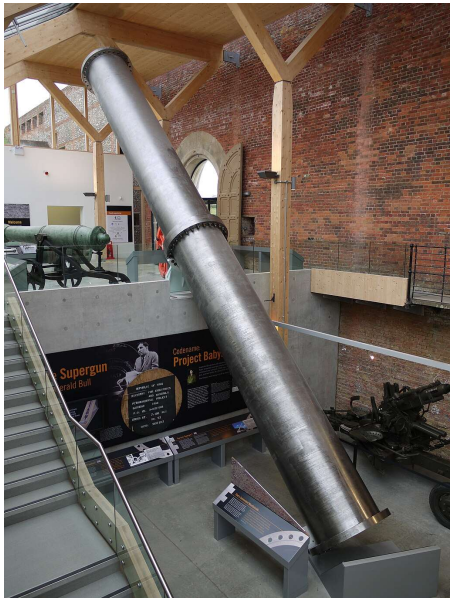
SPINLAUNCH

Space cannons

Cost of going to space

	1 million people	1 billion people
Cost/kg	$284	$284
Development cost	$Billions	$Billions
kg material needed	~50 B	~50 T
Launch cost	$14.2 Trillion	$14.2 Quadrillion
Construction cost	$Billions	$Billions
Development cost	$Billions	$Billions
Total cost	$14.206 Trillion	$14.2 Quadrillion
~	27 mo. US gov.	2.5x world value

Verdict: Not possible??



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Jules Verne, From The Earth To The Moon

GREENLAUNCH

SPINLAUNCH

Skyhook

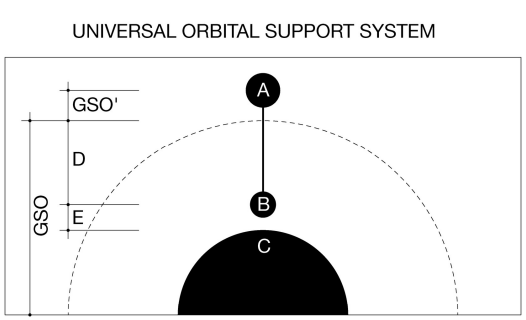
- Development since 1990 (Zubrin)
- Rocket needs 4 km/s Delta-V instead of 9 km/s
  - 75% smaller rockets needed
  - We might even be able to get away with scramjets!

- ~~$333/kg?~~

- **$83.25/kg!**

achieving a HyperSkyhook tether tip rendezvous with a 5.0 km/s (16 kft/s or Mach 16) airplane would require a HyperSkyhook tether mass of 25 times the payload mass. Trying to lower the tether tip speed to 4.0 km/s (13 kft/s or Mach 13) would require a HyperSkyhook tether mass greater than 200 times the payload mass.

Bogar, Thomas J.; Bangham, Michal E.; Forward, Robert L.; Lewis, Mark J. (7 January 2000). "Hypersonic Airplane Space Tether Orbital Launch System" (PDF). Research Grant No. 07600-018I Phase I Final Report. NASA Institute for Advanced Concepts.



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THE MARS SOCIETY

Skyhook

Cost of going to space

	1 million people	1 billion people
Cost/kg	$83.25	$83.25
Development cost	$Billions	$Billions
kg material needed	~50 B	~50 T
Launch cost	$4.163 Trillion	$4.163 Quadrillion
Construction cost	$1.32 B+$100M	$1.32 B+$100M
Development cost	$Billions+$Billions	$Billions+$Billions
Total cost	$4.171 Trillion	$4.163 Quadrillion
~	8 mo. US gov.	41 yrs world GDP

Verdict: Possible at a small scale.

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Total mass of the boost facility is approximately 3,000,000 kg, or about 200 times the mass of the maximum payload mass to be boosted to higher orbit. This very high mass stands out as a

We assume that SPS will only become viable if launch cost gets down to $200/lb, a widely cited number in SPS literature. Therefore we assume a price of no more than $200/lb for SPS launches.

We also need Starship, and to pay the development costs of that, to develop this system.

THE MARS SOCIETY

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Verdict: Possible at a small scale.

Do we do things in half-measures at GT? No!

Rotovator

- Result of Boeing research project
  - Rotation of tether lowers access velocity
  - Hypersonic airliners instead of rockets
  - Stronger materials required due to rotation
- 84%-96% mass reduction
  - https://sites.google.com/view/sources-skyhooks/
  - Split the difference geometrically
    - Assume 92% cost reduction
  - ~~$333/kg?~~
  - ~~$83.25/kg!~~
  - **$26.64/kg!!!**

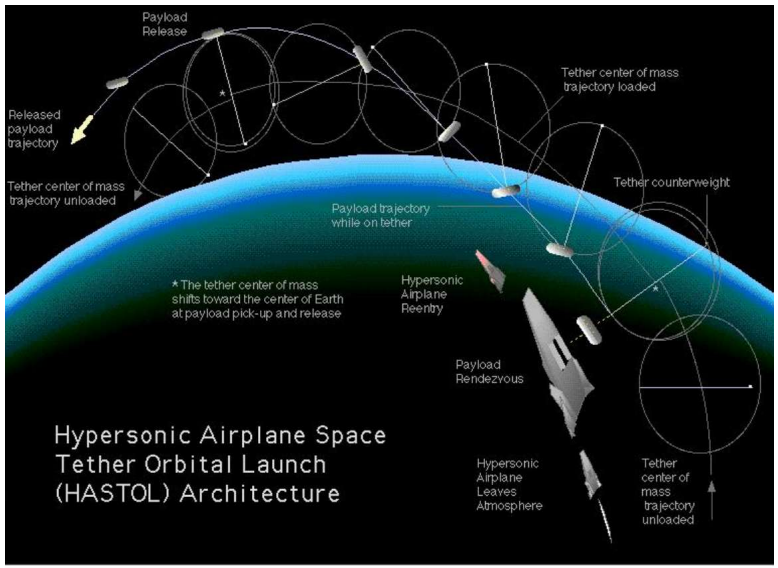

Figure 1. HASTOL System Architecture

- Note – hypersonic research already has lots of funding
  - ASDL-SSDL Collaboration

kurzgesagt

BOEING

Rotovator

Cost of going to space

	1 million people	1 billion people
Cost/kg	$26.64	$26.64
Development cost	~$10 B	~$10 B
kg material needed	~50 B	~50 T
Launch cost	$1.332 Trillion	$1.332 Quadrillion
Construction cost	$Billions+$100M	$Billions+$100M
Development cost	~$10 B+$Billions	~$10 B+$Billions
Total cost	$1.348 Trillion	$1.332 Quadrillion
~	18 mo. US DoD	13 yrs world GDP

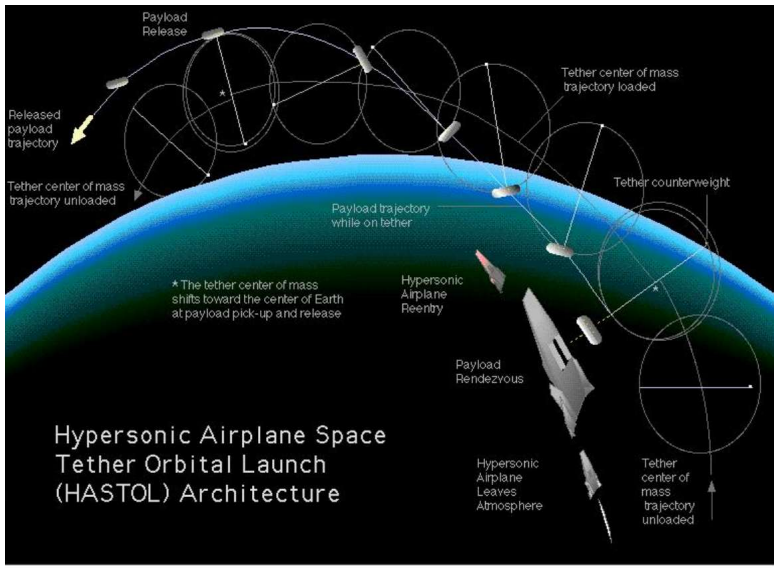

Figure 1. HASTOL System Architecture

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BOEING

Verdict: Possible at a small scale.

Impossible at a large scale??

Launch Loop

- Brainchild of Keith Lofstrom
  - Dynamic support
  - 80 km height
  - 3g electromagnetic accelerator
  - A human-safe space cannon
  - The budget orbital ring!
- Launching decoupled from propellant
  - Electrical mass-drivers instead of explosives or rocket fuel
  - Additional g-hardening unnecessary
- **$3/kg in exchange for $30 Billion initial investment**

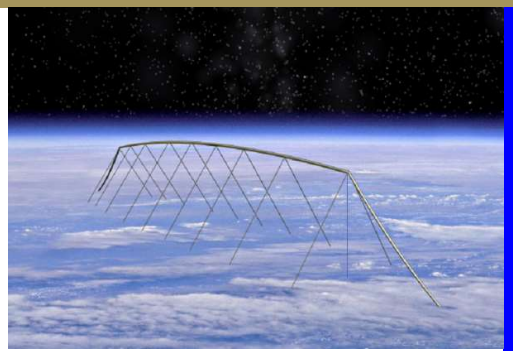
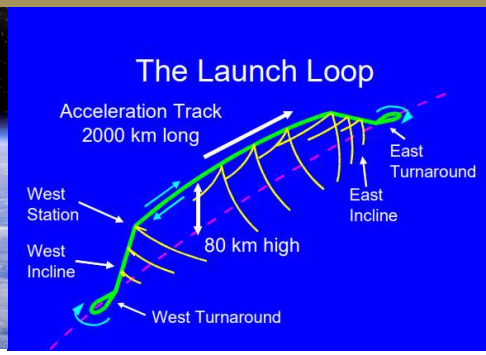


Image from Steve Bowers, Orion's Arm



Keith Lofstrom

Launchloop

Earth to Orbit - and Beyond

SFIA

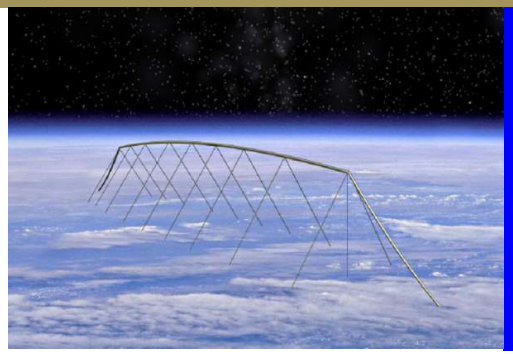
NSS

NATIONAL SPACE SOCIETY

Launch Loop

Cost of going to space

	1 million people	1 billion people
Cost/kg	$3	$3
Development cost	~$10s of Billions	~$10s of Billions
kg material needed	~50 B	~50 T
Launch cost	$150 Billion	$150 Trillion
Construction cost	$30B+$100M	$30B+$100M
Development cost	~$10s B+$Billions	~$10s B+$Billions
Total cost	$213 Billion	$150.063 Trillion
~	86% of Elon Musk	18 mo. world GDP



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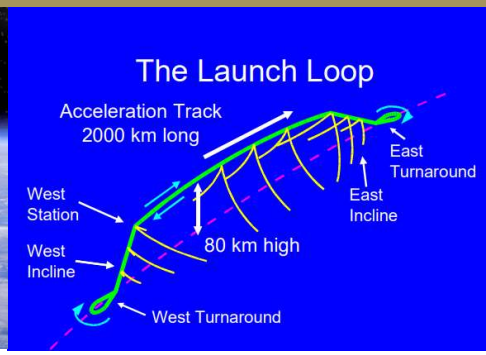

Keith Lofstrom

Launchloop
Earth to Orbit - and Beyond

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Verdict: Inexpensive at a small scale.
Possible at a large scale??

Space Elevator

- Konstantin Tsiolkovsky & Arthur C. Clarke
- Utilizes Earth's spin for launch
  - Can only go to GEO
  - Questions asked about materials
    - Carbon nanotubes
    - Boron nitride nanotubes
  - 54 MJ/kg
    - Can wire the energy with superconductors
- **$1.19/kg in exchange for $100 Billion initial investment**

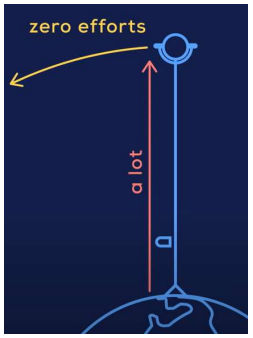

Image from kurzgesagt


Image from Business Insider

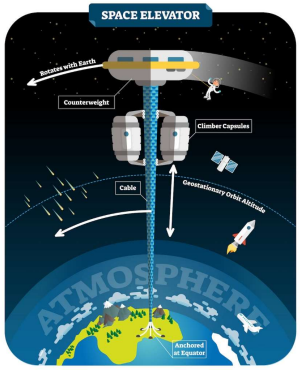

Image from Freethink.com

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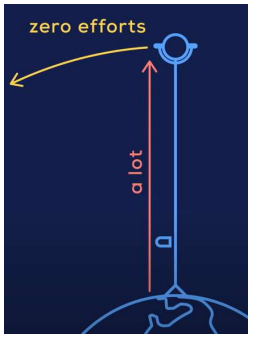
Space Elevator

Cost of going to space

	1 million people	1 billion people
Cost/kg	$1.19	$1.19
Development cost	~$10s of Billions	~$10s of Billions
kg material needed	~50 B	~50 T
Launch cost	$59.5 Billion	$59.5 Trillion
Construction cost	$100B+$100M	$100B+$100M
Development cost	~$10s B+$Billions	~$10s B+$Billions
Total cost	$204 Billion	$59.633 Trillion
~	82% of Elon Musk	28 mo. US GDP



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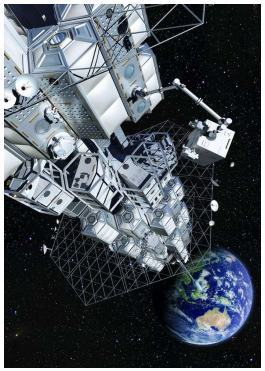
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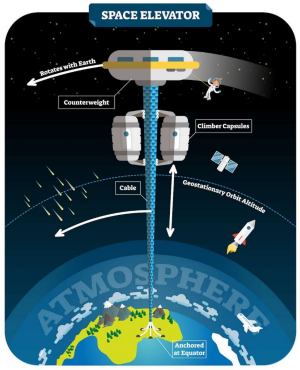


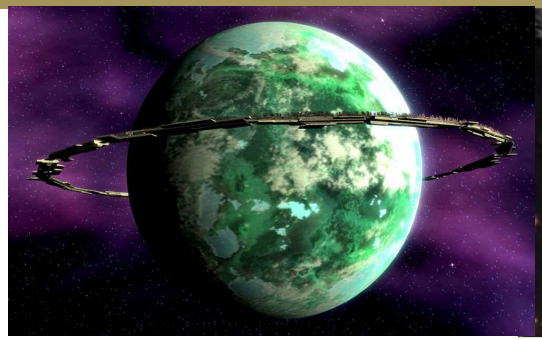
Image from Freethink.com

Verdict: Effective at a small scale.

Possible at a large scale?

Orbital Ring

- Brainchild of Paul Birch
  - Dynamic support
  - 80-1200 km height
  - 2g electromagnetic accelerator
  - Nearly unlimited size
- Prerequisites
  - Launch loop
- Use “Atlas pillars” for transporting materials up the 80-1200 km
  - 31 MJ/kg
- **$0.68/kg in exchange for $1 Trillion initial investment**



Star Wars

Stellaris

THE BRITISH INTERPLANETARY SOCIETY

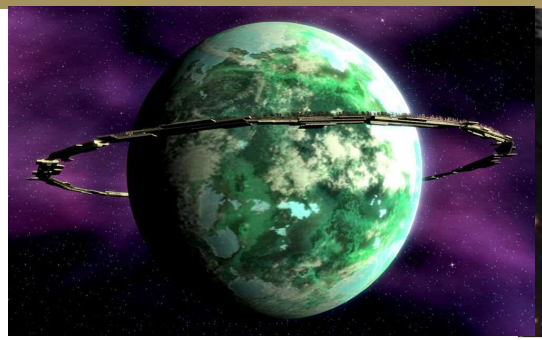
SFIA

NSS NATIONAL SPACE SOCIETY

Orbital Ring

Cost of going to space

	1 million people	1 billion people
Cost/kg	$0.68	$1.19
Development cost	~$100 Billion	~$100 Billion
kg material needed	~50 B	~50 T
Launch cost	$34 Billion	$34 Trillion
Construction cost	$1T+$30B+$100M	$1T+$30B+$100M
Development cost	~$100B+~10Bs+Bs	~$100B+~10Bs+Bs
Total cost	$1.197 Trillion	$35.163 Trillion
~	16 mo. US DoD	98% US gov. debt



Star Wars

Stellaris

Verdict: Overkill at a small scale.

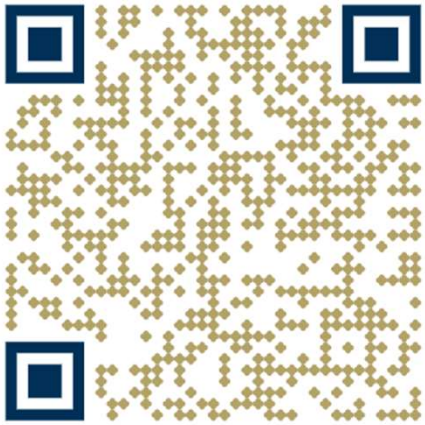
Possible at a large scale.

Summary and Conclusions

Launch system	Future overhead	Cost/kg	Turnover mass	~	Turnover people
Current systems	N/A	$1500	N/A		N/A
Ultra-heavy launch vehicles	$3.1 Billion	$333	2,650 mt	6.5 ISSes	54
Space cannons	$6 Billion	$284	4,930 mt	12.3 ISSes	99
Skyhooks	$7.42 Billion	$83.25	29,700 mt	1.65x everything sent to space	595
Rotovators	$16.1 Billion	$26.64	52,500 mt	2.92x everything sent to space	1052
Launch loops	$63.1 Billion	$3.00	191,000 mt	10.6x everything sent to space	3825
Space elevator	$133.1 Billion	$1.19	401,000 mt	22.3x everything sent to space	8023
Orbital ring	$1.163 Trillion	$0.68	501 million tons	84 Great Pyramids	10.03 million

More information

Questions?



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