# COST-EFFECTIVE AND ENVIRONMENT-FRIENDLY SPACE CARGO ELEVATOR

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Up to today, the only means to reach space remains old-fashioned (from the scientific point of view) propulsion engines, such as chemical, thermal, and cold gas thrusters. These are all expensive and environment-polluting methods based on Newton's third law of motion. In this article, we propose a new, cost-effective, and environment-friendly concept of reaching space - mostly for cargo delivery, although other uses of this method, such as space tourism and others can be considered as well. This new concept (the space cargo elevator) is based on the radiation pressure generated by the laser beams and various engineering concepts. We demonstrate that most of the costs are one-time initial investments, while the running costs are highly competitive. We also demonstrate the exceptional environment-friendliness of the proposed space cargo elevator concept.

## Introduction

We would like to start by answering the “why?” question. It is responded to in the next two sections – “A. The environment” and “B. Launch and other costs”. Section “C. Thrust from the radiation pressure” presents the science behind the space cargo elevator concept.

### *A. The environment*

There is significant research on the environmental damage rocket launchers cause nowadays. This includes pollution of the atmosphere (e.g., with carbon dioxide) and the land with all its consequences, (e.g., ozone layer degradation, acid rain, etc.). It is long overdue to employ an environmentally safe, or at least sustainable, method of shipping a payload to space. In this article, we propose a new concept based on using laser beams, powered by renewable energy, to generate an adequate amount of radiation pressure to lift a payload to space. This new concept is truly environmentally friendly and doesn't cause any pollution whatsoever.[1]

### *B. Launch and other costs*

Nowadays, every rocket launch is achieved by burning a significant amount of fuel regardless of the type of engine. Rockets launched by modern companies such as SpaceX are no exception to this rule. This obviously also adds to the cost of delivery of each kilogram of payload to the space. In the concept we propose, the thrust is obtained from the radiation pressure created at the Earth-facing surface of the space cargo vehicle by the laser beams, which are located on the ground and are powered by renewable energy. Therefore, the fuel costs of traditional rocket engines are absent in our concept and are replaced by the more affordable costs of electricity required to power up laser beams. Also, a fully reusable, light, and simple-construct vehicle is proposed creating a breakthrough cost efficiency for space cargo delivery. It needs to be noted that one-time costs of solar farms deployment, as well as laser system installations, might be significant. One-time costs of space launch complex creation, as well as maintenance costs, do exist as well but are believed to be minimal as the overall complexity of the method is lower compared to traditional methods.

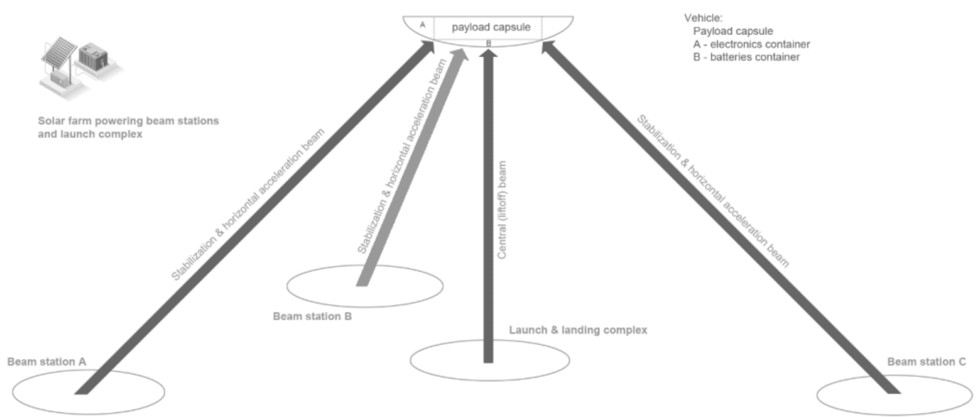


*Figure 1: Schematic representation of the space cargo elevator. Beam stations A-B-C form an equilateral triangle in this simplest setup where there are three stabilization and horizontal acceleration beams.*

As you can see from the above figure, laser beams are being directed at the elevator capsule creating the needed radiation pressure (force). The minimal number of non-central beam stations is three to ensure

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[1] Potential pollution caused by the production of materials for solar farms, launch complexes or space cargo elevator vehicle are disregarded as being irrelevant to the concept presented in this research.

good horizontal stability of the flight. More beam stations can obviously be added. The distance between beam stations (depending on the required orbit altitude and the number of beam stations) will be ranging between 40 and 80 kilometers to provide enough angular value for good horizontal stability of the flight. The following important factors should be considered:

- Beam divergence will play a certain negative effect depending on the equipment used, the size of the elevator capsule, and the altitude, which should be reached. We will speak about relevant altitudes further below in the article. The divergence of a laser beam is proportional to its wavelength and is inversely proportional to the diameter of the beam at its narrowest point. Therefore, for the same beam diameter, a laser beam with a lesser wavelength will have lower beam divergence.
- Thermal blooming of laser beams in the atmosphere should be factored in when considering location options for the space cargo elevator launch complex (dry climate preferred) and the beam characteristics such as power and beam diameter. Additional mitigation can be achieved by increasing the number of beam stations and lowering individual beam power.
- High-quality mirrors, high-precision heliostats-type devices, accurate position tracking devices both on the space cargo elevator vehicle and on the ground, and low-latency communication between all parts of the complex, custom-made software running on high-performant hardware should be deployed to deduce other potential losses of the beam power.

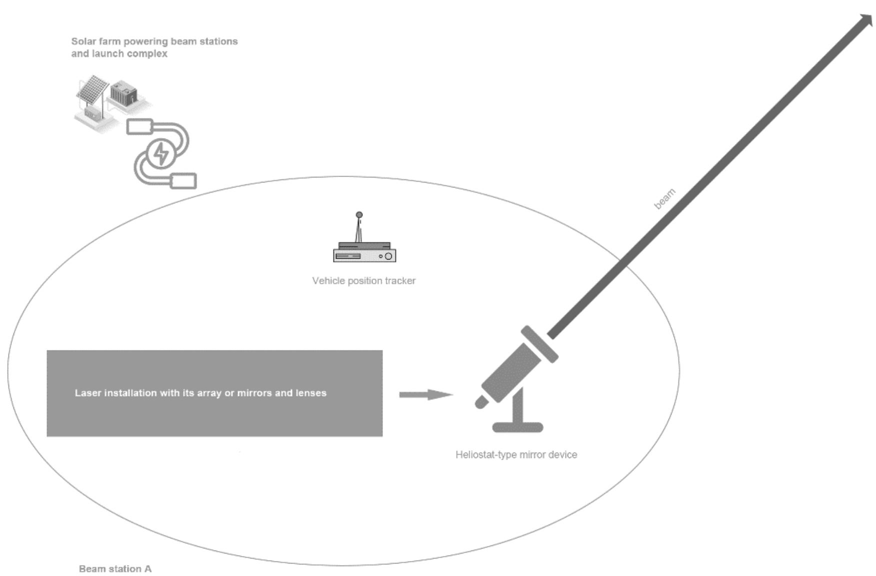


*Figure 2: Schematic representation of one of the beam stations.*

As you can see in figure 2, electricity to power up laser installations is supplied from the solar-powered (accumulated) source. The beam is directed through the high-precision heliostats-type mirror equipment to the exact position of the space cargo elevator vehicle. Precise coordinates of the space cargo elevator are determined using trajectory prediction software supplied with real-time data from the space cargo elevator vehicle's position detector and from an array of ground-based trackers.

There will be a significant amount of electric energy used during the liftoff. This obviously depends on the total weight of the space cargo elevator vehicle with the payload included. Calculations are presented in the below sections for a sample total weight. At the same time, it should be noted that the liftoff operation, depending on the required altitude, will take a few hours and therefore it will be more affordable to have a lower-capacity solar farm with an energy-accumulating engine. New innovative approaches to accumulating solar energy can be explored. For example, Energy Vault[2] stores electrical energy by efficiently transforming it into gravitational potential energy using a large number of 35-ton bricks that can be raised and lowered. This gravitational potential energy can be transformed back to the electrical energy at the liftoff operation for example. Solar farm installation costs are currently between \$0.89 to \$1.01 per watt. That means that, for example, a 1 megawatt (MW) solar farm would cost between \$890,000 and \$1.01 million. These figures are based on the Solar Market Insight Report 2021 Q4 by Solar Energy Industries Association[3]. Regarding the lifetime of laser modules, these are rather significant. For example, typical laser diode module lifetimes are in the range of 25,000 to 50,000 hours.

While precise cost calculations are outside of the scope of this paper, the overall conclusion is that one-time costs of space cargo elevator complex creation can be significant, whereas the operation costs are highly cost-efficient.

### *C. Thrust from the radiation pressure*

Radiation pressure is the mechanical pressure caused on the matter (object) by the exchange of momentum between it and the electromagnetic field. The most intuitive way to understand this phenomenon is by looking at it from the angle of the momentum exchange of the light particles – photons. It is the same momentum conservation law, which dictates that due to the interaction with matter the

[2] Harness the potential of long-duration storage
[3] Solar Market Insight Report 2021 Q4

total momentum change of photons must involve equal-value and opposite-direction momentum change in the interacted matter.

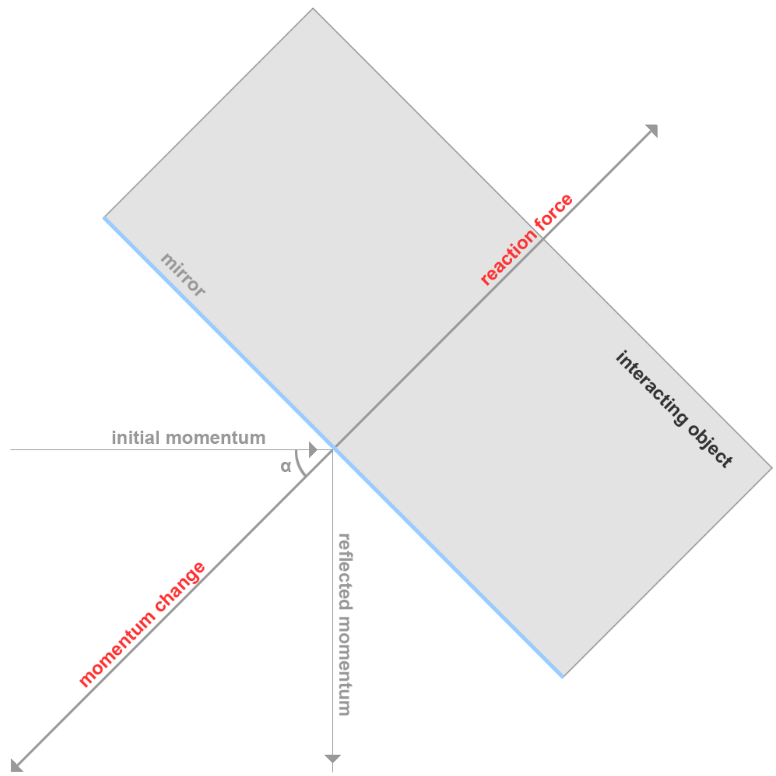


*Figure 3: Momentum exchange between the interacting object having a reflective surface with the "light particles" – photons.*

Light photons' momentum change during the interaction with matter can be caused by reflection, absorption, and emission. Reflection will be the main interaction type we will be researching in this article as it will cause the most thrust compared to other types of mentioned interactions. It needs to be noted that using radiation pressure to create trust is currently actively researched in solar sailing. For the most interesting and relevant examples, we will refer the reader to the IKAROS[4] Japan Aerospace Exploration Agency experimental spacecraft and the LightSail[5] project from The Planetary Society both demonstrating

[4] Small Solar Power Sail Demonstrator "IKAROS"
[5] LightSail, a Planetary Society solar sail spacecraft

successful employment of radiation pressure for thrust generation in space. The associated force is called the radiation pressure force.

While radiation pressure was successfully tested in space solar sail projects, the novelty of our approach is in constructing a space cargo elevator based on radiation pressure force resulting from the Earth-based laser-powered beams.

To conclude the introduction, we point out the necessity of addressing important safety laser beam-related concerns as parts reflected from the elevator capsule beam (or missing the elevator capsule) may cause interference (or pose a direct risk) with objects in the air, space, and on the ground.

## Radiation force vs. Earth's gravitation force

The radiation pressure on the unit of a surface, neglecting emissions, is determined by

$$\boldsymbol{P = \frac{I}{c}(1 - k + p)cos^2\alpha}$$

Where $\boldsymbol{P}$ is the pressure, $\boldsymbol{I}$ is the flux density, $\boldsymbol{c}$ is the speed of light in vacuum, $\boldsymbol{k}$ is the transmittance coefficient, $\boldsymbol{p}$ is the reflection coefficient, and $\boldsymbol{\alpha}$ is the angle between the incoming beam and the perpendicular to the space cargo elevator surface direction as per the figure 3.

We will make the following assumptions to simplify calculations:

1. The surface is **fully reflective**
2. The space cargo elevator vehicle surface is **planar** at **90°** to the incoming beam ($\boldsymbol{\alpha = 0}$)
3. We would like to lift space cargo elevator with a **total sample mass of 10 kg (M)** including the weight of the payload

The formula is therefore reduced to

$$\boldsymbol{P = \frac{2\,I}{c}}$$

The respective force is

$$\boldsymbol{F = A\,\frac{2\,I}{c}}$$

Where ***A*** is the area of the interacting surface. Flux density is the laser beam power ***u*** divided by the area. Therefore, we are arriving at the following formula for force, with the assumption that the laser beam doesn't miss the space cargo elevator surface

$$\boldsymbol{F = \frac{2\,u}{c}}$$

Given the mass of the Earth and the sample object (e.g., 1 kg) one can calculate the gravitational force to be 9.8 N at the Earth's surface for 1 kg mass. The gravitational force, in Newtons, for ***M*** kilograms of weight is

$$\boldsymbol{F = 9.8\,M}$$

Therefore

$$\boldsymbol{u = 9.8\frac{c\,M}{2}}$$

For the sample weight of **M = 10kg,** we, therefore, get the required combined laser beam power of (rounded) ***15 MW***. With the simplest four-beam (the main at the launch complex and three beam stations) each having 4 MW continuous-wave power we can lift the sample weight to the orbit. Pulsed lasers can obviously be used and simple recalculation for the power parameters can be done accordingly.

Low Earth orbit, where most of the satellites are deployed, spans the region of 160 km – 2,000 km altitudes. Depending on the required altitude, a relevant acceleration should be calculated thus fixing the weight of the payload and the space cargo elevator vehicle.

The 1MW solar farm mentioned above can accumulate the required power every two days to lift this sample weight to the orbit with no additional expenses. This should be compared to the traditional costs, which for the same sample weight of 10 Kg are in the range of USD 100,000 to USD 1,000,000.

## Liftoff, orbit, descent, and landing

During the initial state of the liftoff from ground level throughout the troposphere, it is going to be the main beam (from the launch complex) contributing efficiently to the liftoff thrust. Not only the power of one beam is not going to be enough for the radiation pressure propulsion, but the air resistance and horizontal stability of the flight are under question as well. To address these issues, we propose:

1. Add quadcopter technology into the space cargo elevator vehicle for liftoff, the last miles of the descent, and safe landing phases of the flight. Arms with rotors and propellers should be foldable or deployable/removable so that these are not damaged during the re-entry into the atmosphere after orbiting phase of the flight completes. Once flight speed is greatly reduced during the descent by air resistance, propellers should be redeployed. At descent, the weight of the space cargo elevator vehicle is reduced as the payload is left in the orbit, and given its relatively large size (several meters in diameter), one can calculate the expected stable speed in the lower parts of the troposphere noting that the force is proportional to the speed of the decent relative to the air in the power of two:

$$\boldsymbol{F} = \frac{\boldsymbol{1}}{\boldsymbol{2}}\, \boldsymbol{p}\, \boldsymbol{C}\, \boldsymbol{A}\, \boldsymbol{v}^{\boldsymbol{2}}$$

   Here ***F*** is the air resistance force, ***p*** – is the density of air, ***C*** – is the air drag coefficient, ***A*** – is the exposed to the air drag area, $\boldsymbol{v}$ – is speed relative to the air. This force is again compared with the gravitational force to obtain the stabilized speed of the free descent.
2. Include in the space cargo elevator vehicle lightweight batteries, which should provide enough electricity for the quadcopter motors in few first and last minutes of the flight. These will also be used in the case of an emergency landing when a laser beam source is not available for whatever reasons.
3. Include in the fully reflective space cargo elevator vehicle special surface elements, which can physically change the orientation of the surface cell or even fully rotate it with the other-side surface, which is a photovoltaic receiver. Alternatively, on the same spots of the surface, to use liquid crystal panels with varied reflectance, having behind these photovoltaic receivers. See figure 4 for a schematic representation.
4. Above-mentioned special surface elements will be used in the photovoltaic mode during the troposphere phases of the flight to provide electricity to the quadcopter motors. The same elements will be used to improve flight position accuracy as well as counter various rotation issues and/or needs. During the orbital flight phase, these elements will be used to change the amount of radiation pressure to control the flight attitude.

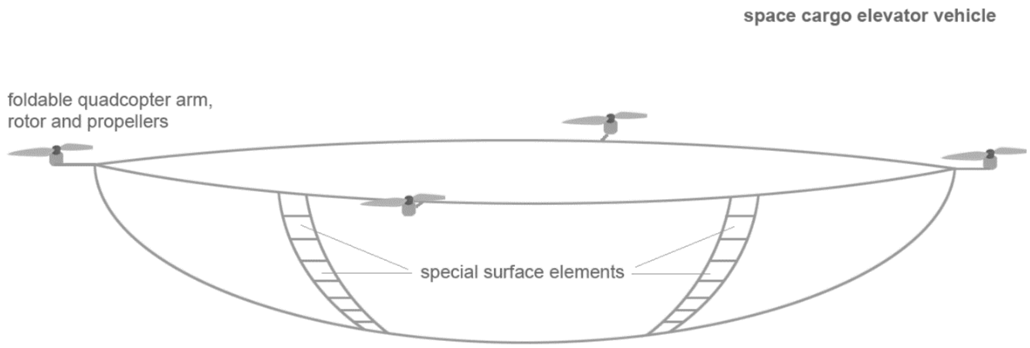


*Figure 4: Schematic representation of: a) the foldable or deployable/removable quadcopter arms with rotors and propellers, and, b) special surface elements with variable reflection and built-in photovoltaic receiver.*

Powering a quadcopter with a laser beam is not a novelty. A portion of the incoming beam is converted to electricity with the help of photovoltaic elements. We refer the interested reader to the following two recent, most relevant, and successful projects:

- Powering quadcopter with a laser beam for 12 hours of flight: "12-hour hover: flight demonstration of a laser-powered quadrocopter"[6]
- Powering ribbon-climbing robot with the laser beam. The winner of NASA's Centennial Challenges - Elevator:2010[7]

The discussed above components, such as liquid crystal panels with varied reflectance, and photovoltaic receivers for laser beams also exist and have passed successful testing in various projects. What will need further work and testing is the materials' endurance under stronger laser radiation conditions.

## Sunlight factor

During the orbiting phase of the flight, the radiation pressure created by the sunlight should be factored in to derive to the correct trajectory. It can be used to correct the altitude as well by using the mentioned special surface elements. Given the low weight of the space cargo elevator vehicle and relatively large

[6] Article and the video footage of the experiment for "12-hour hover: flight demonstration of a laser-powered quadrocopter" project
[7] Elevator:2010

reflective area, the radiation pressure force might be significant. The luminosity of the sun is estimated at:

$$\mathbf{3.846\ 10^{26}}\ \textit{\textbf{watts}}$$

It is radiated in all directions uniformly, which means that a square meter or surface, positioned in the space perpendicularly to the sun radiation beam, receives a power dependent on the angular value it has to the sun as all other equation elements can be considered constants (e.g., the radius of the Sun). For the purposes of our research, we are interested in the distance to the Earth, which is 1 astronomical unit (AU):

$$\mathbf{1\ AU = 149,597,870,700\ meters}$$

This will be an approximation as Earth's distance to the Sun is varying due to its elliptical orbit. Another approximation is in relation to the Sun activity cycles. These do not play a substantive role in our research, and we can confidently proceed with using the solar irradiance at

$$\boldsymbol{G_{sc} = 1,361\ W/m^2}$$

regardless of the time of the year and Sun activity cycles. This is the value at open space, where there are no losses due to the passing of light through the atmosphere. Obviously, the sunlight radiation is available at the space cargo elevator only when the sun is not shadowed by the Earth.

### Various other important considerations

1. Locations with natural highlands with the most sunny days, dry climate, and clean air should be given a preference due to various discussed-above reasons and most importantly related to loses of laser beam related to passing through the air including the laser beam blooming effects. There are countries, which can provide with suitable conditions, for example, several Latin America countries such as Peru, Chile, or other countries, such as Armenia, etc. We refer interested in this topic reader to the National Solar Radiation Database.[8]
2. The exact minimal size of the space cargo elevator capsule is determined by the beam divergence (so that space cargo elevator vehicle can use the beam effectively), which is in its turn depends on the selected altitude of the orbit and the wavelength of the beam. The wavelength will also depend on the safety decisions made. All these interconnected and precise calculations can be done once the goals of the prototype or end-product are decided.

[8] National Solar Radiation Database

3. The software controlling the stability of the flight should be running on both the space cargo elevator vehicle as well as on the ground (to control laser beams). Low-latency data connection between the vehicle and the ground control systems should therefore benefit timely decisions to be made by software.

## References


1. P. Janhunen (2004). “Electric Sail for Spacecraft Propulsion”
2. Kopp, G.; Lean, J. L. (2011). "A new, lower value of total solar irradiance: Evidence and climate significance". Geophysical Research Letters. **38** (1)
3. Thomas Nugent, Jr., Dr. Jordin Kare, David Bashford, Carsten Erickson, Jeff Alexander. ”12-hour hover: flight demonstration of a laser-powered quadrocopter”
4. Geoffrey A. Landis (1991). “Photovoltaic Receivers for Laser Beamed Power in Space”
5. V. Vorob'ev (1991). “Thermal blooming of laser beams in the atmosphere”. Progress in Quantum Electronics, Volume 15, Issues 1–2, 1991, Pages 1-152.
6. Geoffrey A. Landis. “Optics and Materials Considerations for a Laser-propelled Lightsail”