An Orbiting Magnetic Arrest System for Rocket-Free Transportation to Earth Orbit

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The subject of this presentation is a new concept that's intended to reduce the cost of access to space.

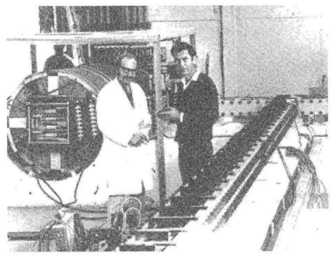
Outline

1. Cannon launch (5 slides)
2. Orbiting arrestor (14 slides)
3. Relevance to renewable energy (6 slides)

One of my areas of research is incorporation of superconductors into electromagnetic launchers. That will be the subject of the first part of the presentation. This work led to the subject of the next part — An orbiting magnetic arrest system is a companion to a launcher. Together, EM launch and magnetic arrest comprise a rocket-free earth-to-orbit transportation method. Finally, I'm going to discuss the relevance of this transportation method to plans to use space solar power to supply clean, renewable energy to earth.

Notable launchers

1960s
HARP
2 km/s, 100 kg
180 km apogee



1970s
University of Canberra
6 km/s, 3 g

1990s
LLNL
8 km/s, 15 g

3

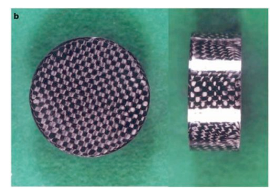
As background, here are some historically important launchers. The cannon in the first picture was part of the High Altitude Research Project, run by McGill University during the 1960s. This project used modified military guns. They were able to repeatably launch 100 kg projectiles to apogees of 180 km. This altitude is high enough for a stable orbit.

The next next picture shows Richard Marshall's rail gun. This experiment generated a lot of interest in EM launch. Railguns can function up to 6 km/s, but the efficiency is poor at speeds above 2 to 3 km/s.

The next picture shows a two stage light gas gun at Lawrence Livermore National Lab. A lab version accelerated 15 g to 8 km/s. The one shown in the picture accelerated about 5 kg to a few km/s. These launchers functioned well, but a launcher that incorporates superconducting materials has the potential to be even better.

Superconducting persistent current magnets

- Because resistance is zero, induced currents flow indefinitely
- Record fields:
  - 3.7 T @ 77 K (Murakami *Phys. C* **357** 751 (2001))
  - 11 T @ 47 K (Gruss et al. *Appl. Phys. Lett.* **79** 3131 (2001))
  - 17 T @ 29 K (Tomita and Murakami *Nature* **421** 517 (2003))



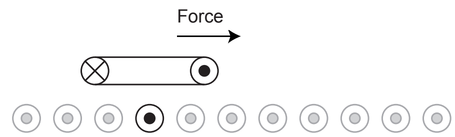
These are pictures of one of the forms of superconducting materials that we can produce in the labs at UH. The picture on the left shows the bare material; the next two show methods of mechanical reinforcement that are used to compensate for the magnetic pressure. These disks can be used in a way similar to permanent magnets, but superconductors can produce much larger fields. A one inch diameter superconducting disk has produced a 17 Tesla field, compared to a maximum of 2 Tesla for the best permanent magnets.

Effects of high fields on machine design

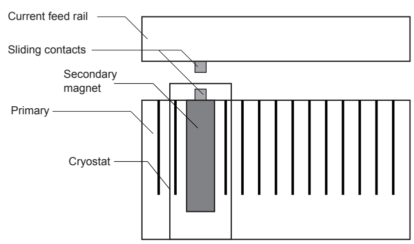
- Improved efficiency
  - Force = BLI
  - Losses proportional to I^2
  - Therefore losses proportional to $1/B^2$
- Sliding contact wear also depends on I^2

Higher operating fields increase the efficiency of electric machines. This is important in itself, but it also helps with one of the main problems that existing railguns have, which is wear in the rails caused by sliding contacts that carry high currents. The difficulty lies in taking advantage of the superconducting materials that are now available. Although processing of long tapes and larger diameter monoliths is possible, presently the only commonly available form of the material is small monolithic disks. After working on several types of launchers, I've arrived at a launcher topology that exploits the available material.

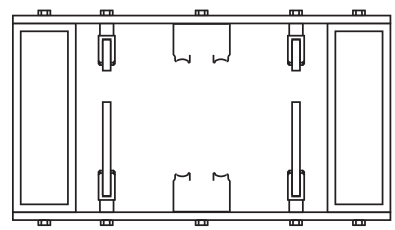
UH launcher topology



Concept, Top view



Side view



Cross section of test launcher

U.S. patent application #20050285452

The first drawing shows the abstract concept for the UH launcher. A loop of current, which can be either a coil of wire, a permanent magnet, or a superconducting disk, is accelerated by an adjacent current in the stationary part of the machine. The less abstract drawing in the lower left shows that the current in the stationary part flows in teeth in a copper sheet, and sliding contacts are used to synchronize the current with the motion of the moving part. The drawing in the lower right shows the cross section of the actual test launcher, which has two copper sheets so that no torque is produced on the moving part, and linear bearings in the middle.

This topology has several good features: It relies on a sliding contact for synchronization, which has been shown to work efficiently up to speeds over 2 km/s. The high field further improves the efficiency and reduces the wear on the sliding contacts. The elements that must be commutated by the sliding contacts have very low inductance because they are short and thin.

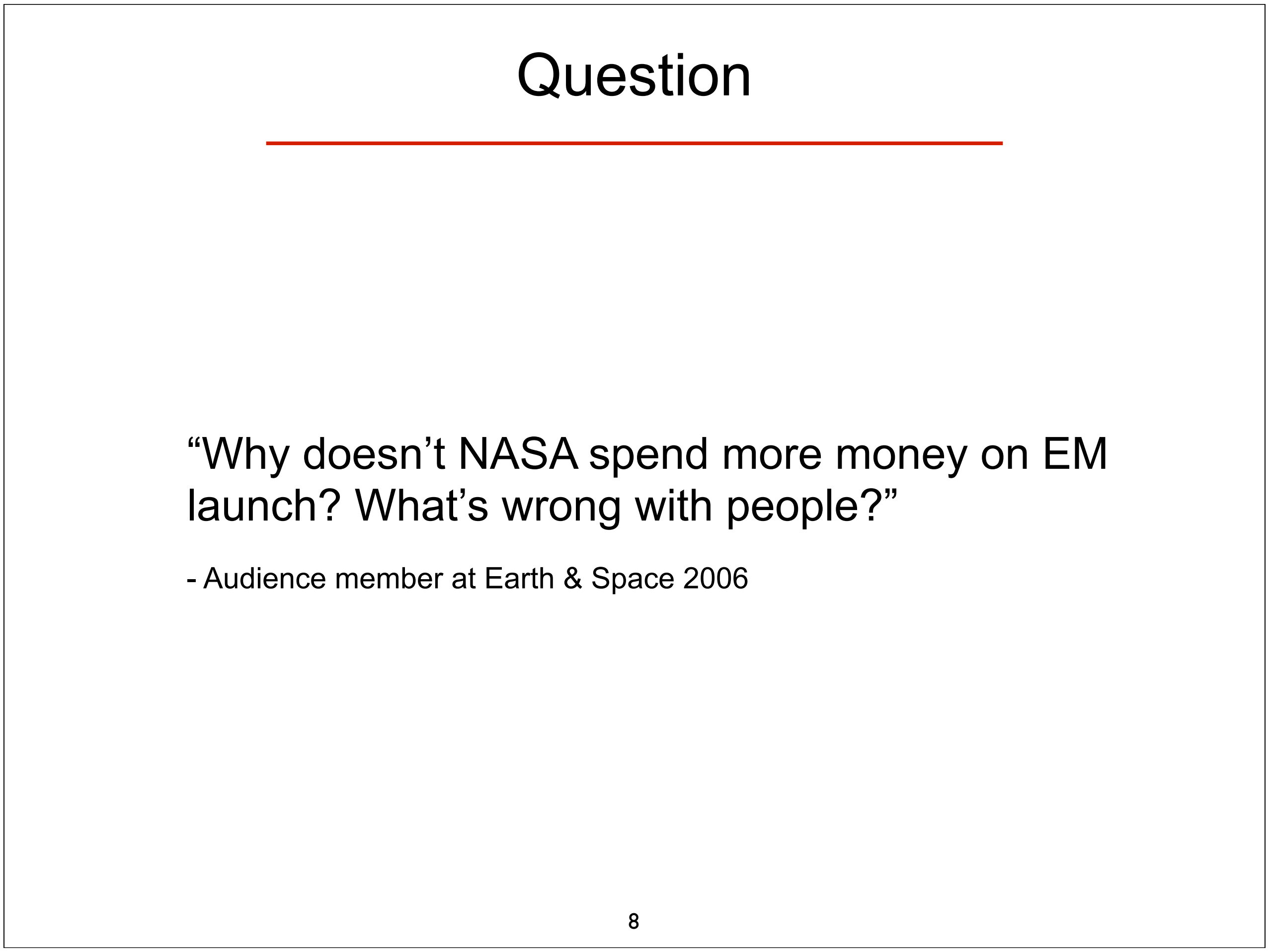
UH launcher

Launcher

Capacitor bank and instruments

1 kg accelerated mass
Speed after gas gun: 130 m/s
Speed after third stator segment: 200 m/s

These are pictures of the test setup. The total length of the launcher is 3 meters. There's a gas gun in the foreground that initially accelerates the projectile, and then the electric part, which is powered by the 20 kJ capacitor bank, takes over. The system has undergone testing to 20 m/s. It is in the process of being upgraded, and should now be capable of 200 m/s. If testing up to 200 m/s works out, and I anticipate that it will, the next phase is to further upgrade the system for operation up to 2000 m/s.



After I gave a presentation on EM launch at a conference earlier this year, a perceptive audience member asked this question. The superconducting launcher might be an improvement on existing launchers, but cannon launch worked pretty well as early as the 1960s. There's been some funding since then, at times quite significant, but the amount doesn't seem to be proportional to the potential. Why not?

Answer

Not because

acceleration is too high for practical payloads

atmospheric heating too much for heatshield materials

politics

It isn't because the acceleration is too large to launch useful payloads. Raw materials are clearly okay, and appropriately selected electronics also survive launch — The HARP cannons launched electronics and specially designed mechanisms, and the U.S. military regularly fires electronics out of guns. Atmospheric heating is not a problem, at least at speeds up to 2000 m/s — The HARP ballistic gliders had metal nosecones. I don't think that the reason is completely political, although that certainly plays a part. I think that the answer is mostly technical.

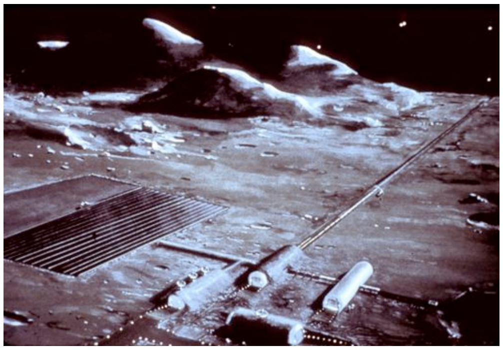
Answer

Cannon launch at <2000 m/s isn't that helpful

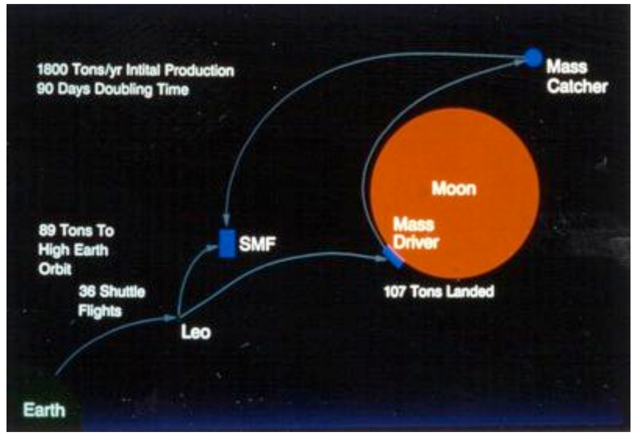
Going faster than 2000 m/s is difficult

In my opinion, the answer to the question is that cannon launch to space is not actually very helpful as long as a rocket is still necessary to provide a significant amount of the velocity needed to circularize the orbit. For LEO, this speed difference is about 8 km/s. During HARP, cannon launched orbital vehicles were designed, but their payload fraction was only about 10%, despite the fact that the cannon had accelerated them to an altitude of 180 km. It is possible for launchers to operate at speeds greater than 2 km/s, but more problems arise, and cannon launch becomes less attractive. I think that another component needs to be added to the system to make cannon launch compelling.

SSI concept



Mass driver on moon

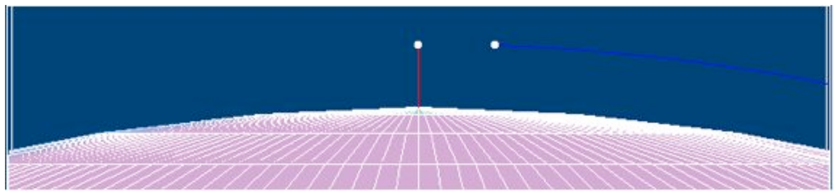


Launch from moon
to mass catcher

From ssi.org

Many good ideas can be found in the SSI settlement plans from the 1970s. The SSI plan for using lunar resources included a satellite that would catch material launched from the moon. They called this satellite a mass catcher (shown in the upper right). One of the drawbacks of this plan is that it required a significant amount of initial mass to be launched to the moon, which might have seemed plausible at a time when there was an expectation of a fleet of cheap space shuttles. (This plan only requires 36 shuttle flights because of clever use of in situ resources!)

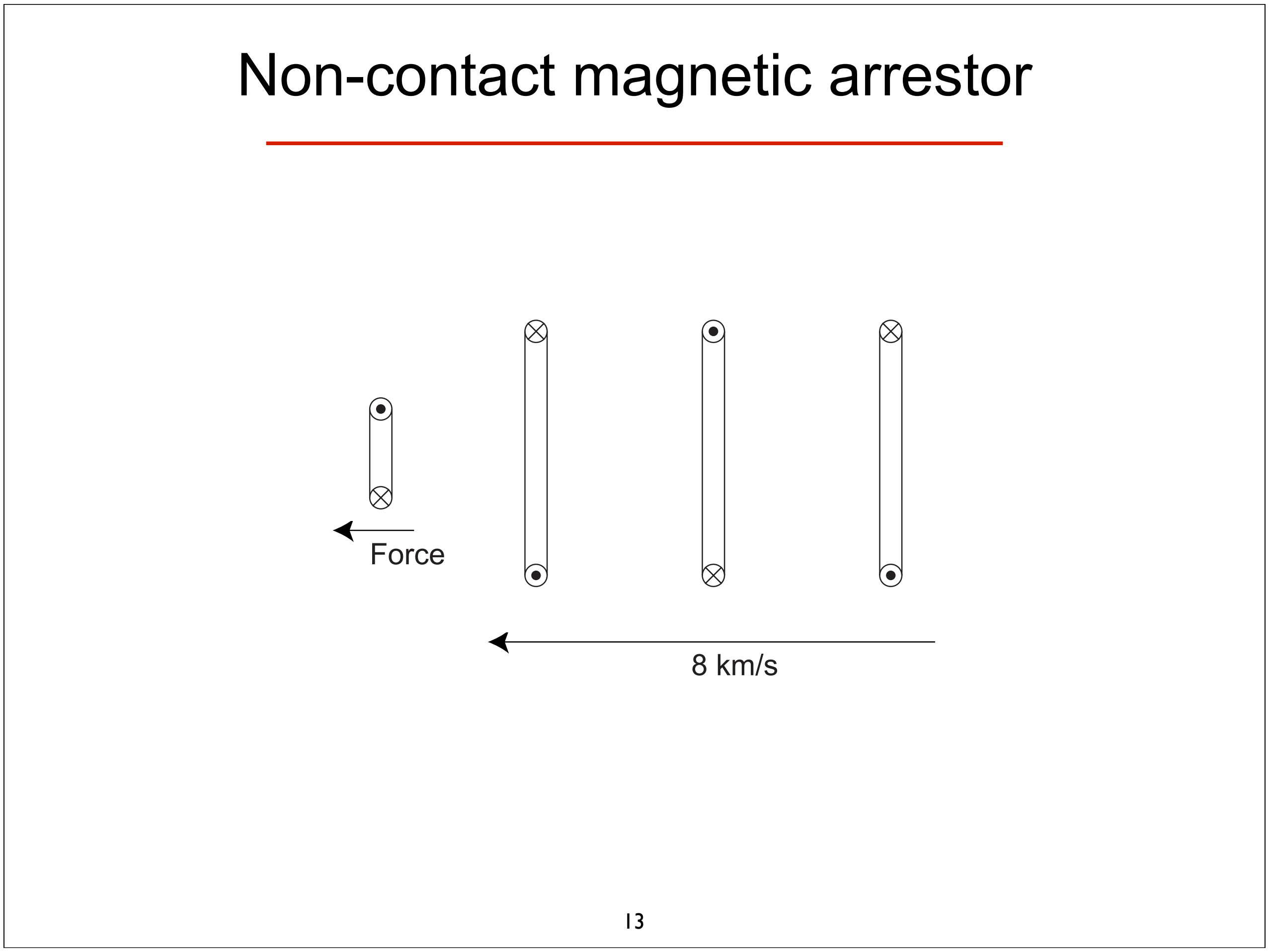
Mass catcher orbiting earth



Arrestor decouples transport to orbit
into two easier tasks

A mass catcher could be placed in orbit around the earth. In this cartoon, which is to scale, the cannon launches the projectile to an altitude of 200 km. At the apogee, the mass catcher comes along and accelerates the projectile from stationary to orbital speed, which is about 8 km/s.

This separates transportation to orbit into two more manageable tasks: launching a projectile to an altitude of 200 km, and maintaining an orbit.

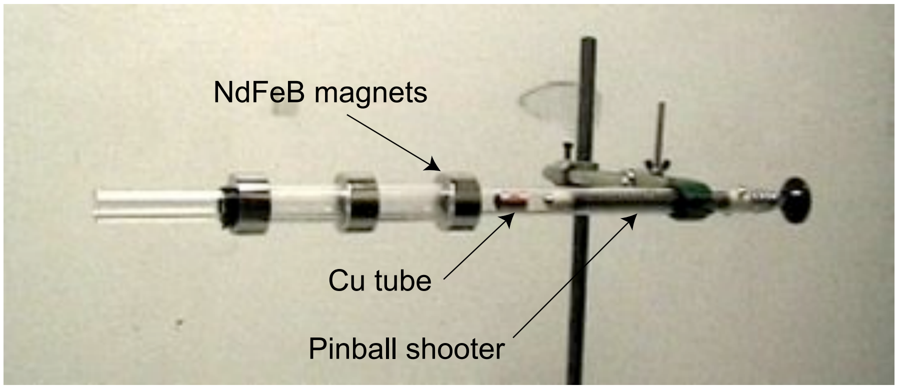


The SSI mass catcher obliterated the payloads, which was acceptable for the original purpose of catching lunar regolith. However, for general use, it would be better if the catcher could use a non-contact method. On Thursday, I found out that Peter Schubert has also been thinking along these lines, and has a nice idea for an improved mass catcher. Dr. Schubert's catcher uses iron in the projectile, while mine uses Cu or Al. His catcher operates sort of like a reluctance motor, and mine operates sort of like an induction motor. I think that my idea can produce higher accelerations because the induced current pulse can be very large. Also, the best material for the conductive ring that the projectile carries is aluminum, which has a weight advantage over iron.

The concept is simple: as the orbiting magnets, on the right, approach the projectile, each one induces a current in the conductive ring in the projectile (on the left). The projectile is repelled as a magnet approaches, and attracted just after the magnet has passed. After a series of magnets has passed, the projectile has been dragged up to the same speed as the orbiting arrestor.

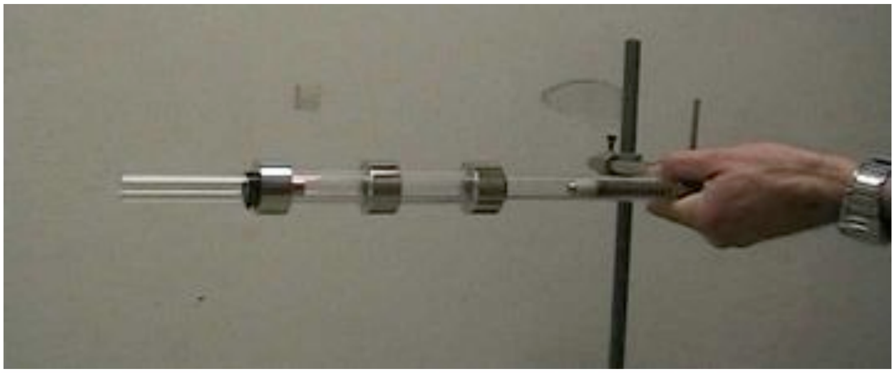
The operation of this system is passive. It is therefore simpler than a stationary launcher that would accelerate a projectile to the same speed. An available high-efficiency propulsion system, such as an ion thruster, can be used to make up the decrease in momentum caused by accelerating the projectile.

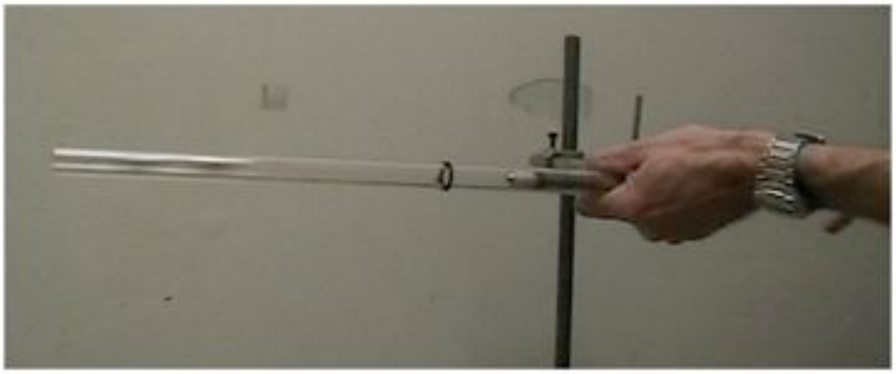
Demo setup



I think that it's a good practice to test new ideas as quickly and cheaply as possible, even simple ideas such as the arrestor. This toy experiment consists of a pinball shooter, which gives a piece of copper tubing a repeatable initial speed, and three strong permanent magnets. The magnets should stop the copper tube, which is equivalent to the situation in the proposed arrestor, in which moving magnets accelerate an initially stationary tube.

Demo





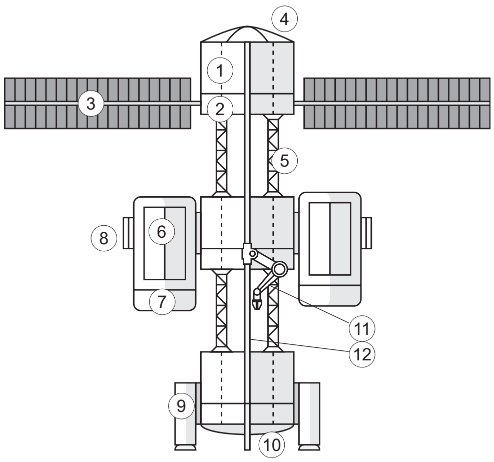
In the movie at the bottom, the magnets have been removed. I repeatedly tried shooting the copper tube, and it always left the clear plastic tube and bounced across the floor. In the movie at the top, the magnets stop the tube. In testing, sometimes they stopped it after the first magnet, sometimes after the second, but the copper never left the plastic tube. I've proven, at least to myself, that the concept is basically sound.

Feasibility

- Dimensions and magnetic field of arrestor
- Dimensions and mass of projectile current loop
- Stability of payload during arrest
- Accuracy of launch
- Rate of delivery of mass to orbit (limited by stationkeeping)
- Suitable payloads
- Testability
- Political considerations

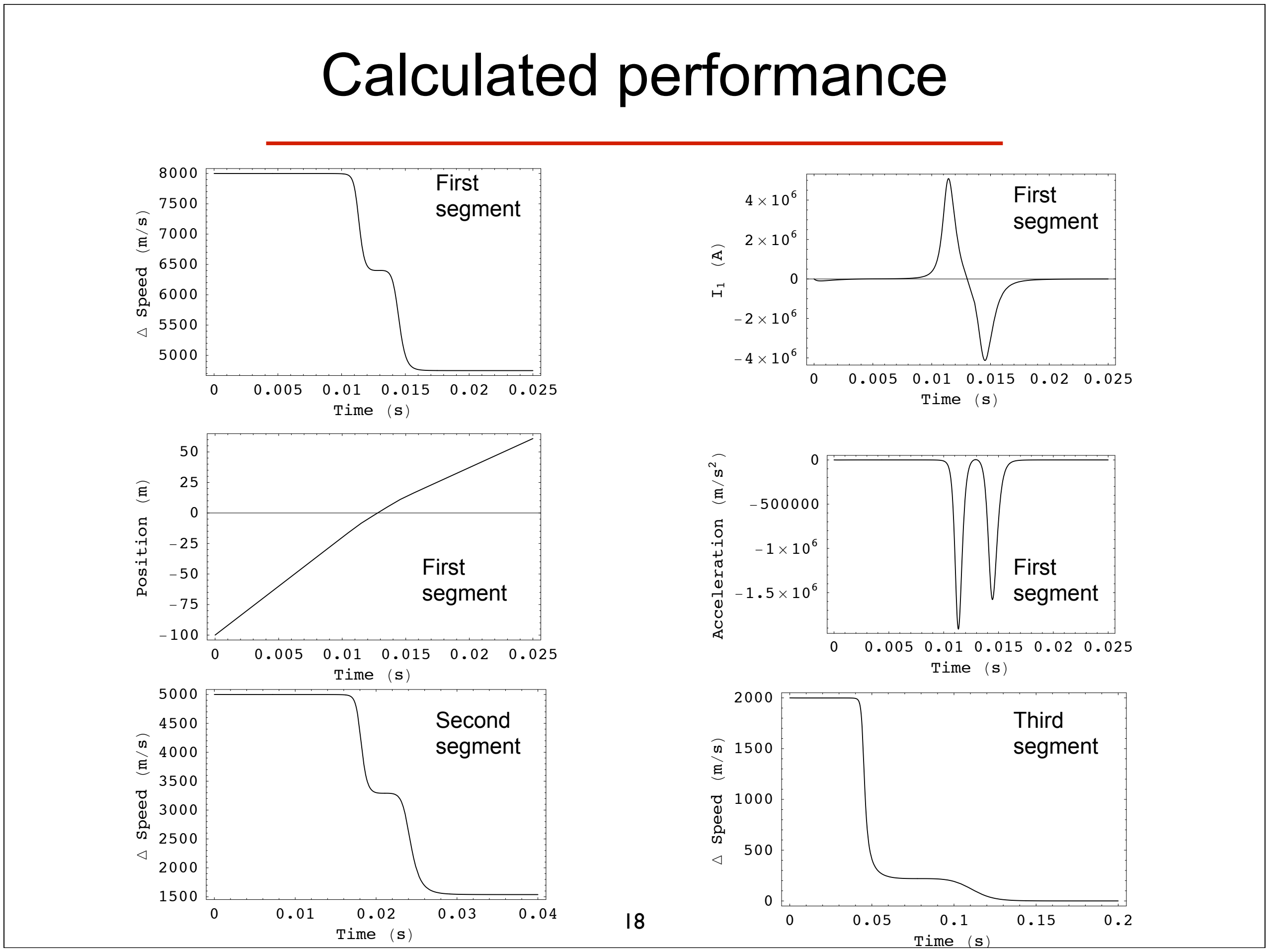
There are many technical details that need to be addressed before concluding that the orbiting arrestor is feasible. The main ones are shown here. All of these items have been considered; I'll present an initial assessment of some of them in the slides that follow.

First estimate



Parameter	Value
Projectile mass	20 kg
Projectile conductive loop diameter	1 m
Number of arrestor solenoids	3
Arrestor solenoid diameter	10 m
Arrestor solenoid length	20 m
Arrestor solenoid winding thickness	2 m
Arrestor solenoid current density	4000 A/cm^2

This is a first guess at the size and performance of the arrest system. The estimate uses a projectile mass of 20 kg. The diameter of the solenoids in orbit is 10 m. This diameter is set by stability and accuracy requirements, which require further study, but I think that 10 m provides a reasonable clearance. The current density that I've used in the magnets is within the capabilities of available superconductors.



These plots show the performance of the arrestor calculated using a simple model. The first of the three magnets in the arrestor brings the speed difference between the projectile and the arrestor to about 5 km/s. The second segment reduces the speed difference to about 2 km/s, and the third reduces the speed difference to zero, i.e., the projectile is now in orbit, traveling 8 km/s along with the arrestor. The current that's induced in the projectile's conductive loop by the first magnet is large, but within the material's limits. If this current is later found to be too high, it can be reduced by adding more magnets to the arrestor to bring the projectile up to speed more gradually. Induced currents and accelerations associated with the second and third magnets are much smaller than those associated with the first magnet.

Testing

- Use launcher to fire projectile into stationary arrestor
- Examine
  - stability
  - centering forces
  - material behavior
- Also study repeatability of cannon-launched trajectories

Testing can be performed in a way similar to the demo, by firing a projectile into an arrestor. The projectile is initially moving and the arrestor is stationary, which is the converse of the situation in orbit, but the behavior should be equivalent. This provides a convenient method of testing the behavior of the projectile during arrest. The conductive ring in the projectile should be self aligning, provided that it is placed behind the center of mass of the projectile.

Implementation

- Launch on Delta, Atlas, Falcon, etc.
- All key components are available
- Cost is within range of private funding
- After initial investment, operating cost is very low

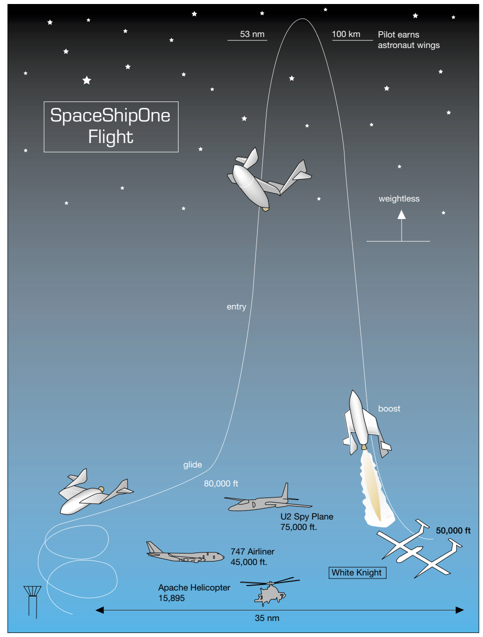
The great thing about this concept is that it can be implemented by a few launches of existing vehicles, which puts it within reach of private funding. Being just a university researcher, I don't expect to have a significant impact on policy, so I was delighted to realize that there might be a technological solution to the problem of expensive space access that doesn't require an initial effort that only a government could afford. The major components of the system all use existing technology, so, with adequate funding, the development time could be short.

Human payloads

5 gee acceleration limit implies:

- Launcher length of 40 km (for 2 km/s)
- Arrestor length of 640 km

Could also use arrestor with other launch methods, e.g., SpaceShipOne

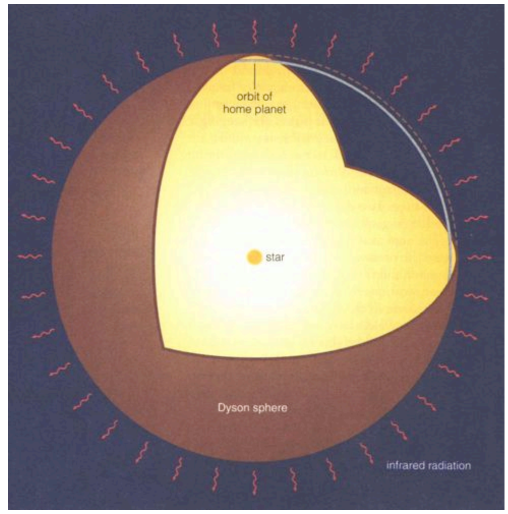


Thus far I've only discussed transportation for non-biological payloads. The concept is applicable to human payloads as well, but the ground based launcher and the arrestor must both be longer. A maximum acceleration of 5 gees implies a launcher length of 40 km and an arrestor length of 640 km. Because the acceleration is lower, the operating magnetic field can also be lower. (640 km is pretty long, but it doesn't sound that bad compared to a 100,000 km space elevator.)

An arrest system for inanimate objects could be used for transportation of components of the lower acceleration system.

Space solar power

- We need at least 10 TW from a clean energy source
- The sun produces 3×10^{17} TW of power
- 165,000 TW of sunlight hit the earth



The combination of increasing population, increasing energy consumption due to higher worldwide standards of living, and decreasing petroleum production create a large need for new power sources. One of the sources that has received attention is space solar power. A solar array in geosynchronous orbit around the earth receives sunlight 24 hours per day. Furthermore, the sunlight isn't attenuated by the atmosphere, or blocked by inclement weather. The power can be transmitted back to earth using microwaves or lasers.

In the long term, it clearly makes sense to develop space. That's where all of the raw materials and energy are. However, in the short term, in order to be developed, space solar power must offer some advantage over terrestrial renewable energy. The next slides compare the return on energy invested in building the two alternatives, including the energy required for transportation to space by either rocket or launcher + arrestor.

SSP energy produced/energy invested

From Pearce and Lau, "Net energy analysis for sustainable energy production from silicon based solar cells," *Solar Engineering 2002*, pp. 181–186:

- 1 m^2 on rooftop in Boulder produces 27,000 MJ over 30 year lifespan
- 1800 MJ are required to produce PV

The solar constant is about 1370 W/m^2 one A.U. from the sun:

- If PV is 10% efficient and transmission is 50% efficient, 1 m^2 in space produces 65,000 MJ over 30 years
- Use 0.5 m^2/kg as estimate for collector and transmitter mass

From a paper by Pearce, the amount of energy that a solar cell produces when placed on a roof in a location with average insolation, Boulder, Colorado, is 27,000 MJ. (This is for a 10% efficient cell.)

Based on some slightly optimistic assumptions, a solar array placed in geosynchronous orbit can transmit about 65,000 MJ to earth during its 30 year lifetime.

Both the solar array on earth and the solar array in space embody about 1800 MJ.

Energy consumption of Delta IV Medium

Payload to LEO: 9106 kg

Payload fraction: 3.6%

Propellant: LOX and LH2

First stage propellant: 199,640 kg

Upper stage propellant: 21,320 kg

Total hydrogen mass: 31,619 kg

Total oxygen mass: 189,341 kg

Specific energy of hydrogen: 140 MJ/kg

Energy to liquefy H2: 30 MJ/kg

Energy to liquefy O2: 2.52 MJ/kg

Energy to LEO: **579 MJ/kg**

Energy in LEO: 50 MJ/kg

=> Energy conversion efficiency = 9%

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For the case of solar arrays in space, a significant amount of energy is also required for transportation. A Boeing Delta IV burns 579 MJ worth of fuel for each kilogram transported to low earth orbit.

After getting to LEO, only about another 10 MJ is required to move to a geosynchronous orbit. This maneuver can be performed by a high efficiency orbital tug.

More energy consumption

First stage structure: 26,760 kg

Upper stage structure: 2850 kg

Energy to refine Al: 46 MJ/kg

Embodied energy / mass to LEO:
150 MJ/kg

Fuel from previous: 579 MJ/kg

Total: **729 MJ/kg**

(=> Energy conversion efficiency = 7%)

Delta IVs are expendable, which means that in addition to the fuel, the energy used to produce the rocket must also be taken into account. A large and easily estimated part of this total is the energy used to refine the metal in the rocket's structure. Assuming that the majority of the structure is aluminum, this adds another 150 MJ per kilogram transported to orbit, for a total of 729 MJ/kg. This estimate excludes many other large energy inputs, making the 7% energy conversion efficiency optimistic.

Cannon launch energy use

Cannon efficiency: 50%

Arrestor stationkeeping efficiency: 50%

System energy conversion efficiency: 50%

=> Energy to orbit: **100 MJ/kg**

Transportation to orbit using the cannon + arrestor system also requires energy. If the system were 100% efficient, it would require 50 MJ per kilogram transported to low earth orbit. Nonsuperconducting motors often have peak efficiencies over 80%. The efficiency of the launcher design I'm studying depends on the length, and for a launcher on the order of tens of meters, I expect an efficiency of about 50%. (A longer launcher is more efficient.) The energy that the arrestor transfers to the projectile is made up by stationkeeping propulsion. A reasonable number for ion thruster efficiency is about 50%. The overall system efficiency is a weighted average (not a product) of these two, so the overall efficiency is 50%, making the energy to orbit 100 MJ/kg. This is a factor of seven better than the rocket. I think that the rocket estimate is optimistic, and the cannon launch estimate is somewhat pessimistic.

Net energy gain

- Terrestrial returns 15X energy investment
- Space PV with rocket returns 20X energy investment
- Space PV with cannon + arrestor returns 30X energy investment

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For the solar array on earth, the energy produced over the array's lifetime divided by the energy used to produce the array is about 15. A solar array in space transported from earth by rockets returns about 20 times the energy invested. The optimistic assumptions make this an upper bound, and it is very difficult to improve the energy conversion efficiency of rockets. Using the cannon + arrestor system for transportation improves the return to a factor of 30, significantly better than terrestrial solar power.

Summary

- Existing cannon technology can launch projectiles to LEO altitude
- Contactlessly accelerating projectiles from LEO altitude to orbital velocity appears feasible
- Energy conversion efficiency of cannon launch + magnetic arrest is much better than that of rockets
- Operating costs are expected to be correspondingly lower
- Initial costs are within reach of private funding
- The cannon + arrestor system makes launch of solar power satellite components from earth energetically favorable

In summary, using a magnetic arrestor with cannon launch from earth appears to be a promising method of reducing the cost of access to space. One example of the effect of the cannon + arrestor system on mission economics is the case of space solar power. Because of the potential high efficiency of the cannon + arrestor, solar power satellites in geosynchronous orbit built using components launched from earth can have a better return on energy invested than terrestrial solar power systems.