A Space Pier

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Abstract

I present a systems analysis and reference design for a structure which could significantly reduce of access to space. The structure consists of a tower, 100 km tall by 300 km long, which would have an electromagnetic launcher along the top. Such a tower could be fabricated with polycrystalline diamond for compression members and currently available polymers for tension elements. Linear induction or similar motors would be used to accelerate the payload to orbital velocity.

A reference design, presented here, calls for 10 tonne payloads accelerated at approximately 10 G's to LEO. Variants, possibly the same tower operating in different modes, could launch smaller packages to Earth escape velocity at 20 G's, or into transfer orbits to Mars or Venus at 30 G's.

1 Background and Overview

Tsiolkovsky first conceived the notion of a static structure allowing access to orbit on seeing the Eiffel Tower. Since that time, numerous variants on the idea have been studied, the most popular being a synchronous satellite having a tension member reaching Earth's surface.

However, a considerably smaller structure using materials available with technology closer to the state of the art is possible, which would provide inexpensive (non-rocket) access to LEO. The structure would be a tower, 100 km tall by 300 km long, which would have an electromagnetic launcher along the top. I refer to such a tower as a space pier since, like a pier for water ships, it extends just to the point where the vessels it services can operate.

Such a tower could be fabricated with polycrystalline diamond (commercially available for 50 years, although not in appropriate quantities) for compression members and currently available polymers for tension elements. A linear electromagnetic motor would be used to accelerate the payload to orbital velocity.

At 100 km altitude, the atmosphere is approximately one part per million of sea-level density. Thus, 100 km is an optimal launch height, as the atmosphere is rarified enough to allow lateral launch into a Hohmann transfer orbit to LEO, but dense enough that the tower would not interfere with existing (or reasonably foreseeable) orbital operations, and would be safe from orbital debris.

A reference design, presented here, calls for 10 tonne payloads accelerated at approximately 10 G's to LEO. Variants, possibly the same tower operating in different modes, could launch smaller packages to escape velocity (and Lunar transfer orbits) at 20 G's, or into transfer orbits to Mars or Venus at 30 G's.

The launch vehicle is accelerated at the top of the tower at 100 m/sˆ2 for 77 seconds to about 8 km/sec. This places it in an orbit with a 100-km perigee and 400-km apogee (with an assist from Earth's rotation and despite some atmospheric drag). This can be corrected to a circular 400-km orbit with 90 m/s delta-V.

The energy required at the launch tower is 300 GJ (under $5000 at $0.05/kWh, again for a 10 tonne payload), or under 50 cents per kg, plus transmission and conversion inefficiencies. Power requirements ramp from 0 to 8560 MW over the 75 seconds; note however, that energy storage (and release) requirements are constant per track length and amount to 1 MJ per meter. A 2000 MW generating facility could support a launch interval of 150 seconds.

Power could alternatively be provided by solar power satellites (launched by the tower itself in a bootstrap mode) into rectennas directly along the track itself. Solar power satellites could be an economically effective early use of tower launch capacity. This idea was current in the 1970's before the extreme cost of current launch systems became apparent. It would regain viability if tower launch costs are low enough.

Launch costs are a function primarily of launch rates and tower cost (including power plant or satellite construction as part of the total project). Amortized capital costs, if financed at 8% and launching at once per hour, would be under $1 per kg per billion dollars of tower cost.

2 Comparisons with related concepts

2.1 Electromagnetic launch

Electromagnetic launch tracks as launch assist, or virtual first stage, from earth's surface, have a long history. It was typically assumed that such a track would be built up a mountainside, but some proposals have envisioned artificial towers in such a role.[1]

The other major precursor concept is the Lunar mass driver that was a part of the O'Neill space colony systems designs.[2] This was the first serious engineering design to envision electromagnetic launch as the sole motive agent for orbital access, albeit from the Moon.

The space pier is in essence a unification of the two ideas. It has the advantage, with the mass driver, of operating effectively in vacuum, and placing payloads directly into orbit. Like the O'Neill drivers but unlike launch assist tracks, the space pier could launch essentially inert, non-spacecraft, payloads.

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[1] see http://www.affordablespaceflight.com/spaceelevator.html, section 3.3.3: Tall Tower Applications

[2] O'Neill, Gerard K, *The High Frontier*, Morrow, New York, 1977

For example, a coilgun version could probably be designed that could launch standard steel cargo containers.

Like launch assist tracks (typically envisioned as maglev/linear motor configurations instead of coilguns), the space pier would operate from the Earth's surface, and connect directly with standard freight and passenger transportation networks. Unlike some of the (particularly mountain-based) schemes, however, it would be feasible to site it in or near populated areas. Besides not needing a mountain, the footprints of the tower structure are small and far apart enough that it would not occupy significant real estate. There would be no noise or other environmental impact, and minimal downrange hazard compared to rocketry.

2.2 Geostationary elevators

The space pier has much in common with the space elevator concept:[3] it is a stationary structure that utilizes electric motor technology to provide low-cost orbital access. It relies on advanced materials properties generally thought of as a concomitant of nanotechnology.

As such, there are many enabling technologies that would be beneficial to both concepts. In particular, nanotech-based manufacturing would reduce the cost of the advanced materials to the point that the structure could be economically viable. Advances in power generation, microwave or optical power transmission, power switching, and electric motor technologies would be similarly beneficial.

Both concepts are based on a notion of economy of scale for inexpensive orbital access, and would benefit from the synergy of a broader market for space access.

The elevator has some advantages over the pier: it launches without high acceleration, and therefore could handle fragile payloads; it provides "native mode" access to GEO as opposed to LEO, where the pier would require booster rocketry and/or human-intolerable accelerations.

However, the pier has significant advantages or its own. It can be built from the ground up, requiring no rocket launches at all for its construction. It could be built anywhere on Earth, where the elevator is limited to near-equatorial sites.

The space pier could be built with materials available today, notably polycrystalline CVD diamond. I hasten to add that like the case of the elevator, such materials are not available today in either the quantity or the price that is needed for feasibility, so development is needed. Note that the elevator and the pier would use the same amount, in orders of magnitude, of advanced carbon material.

Elevator studies indicate that the ribbon could be expected to be struck by one major satellite per year, on the average. Either scheme would probably produce a great increase in space travel, so we might realistically expect this

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[3] see, e.g., Edwards, Bradley C.: *The Space Elevator: NIAC Phase II Final Report* at http://www.liftport.com/files/521Edwards.pdf

problem to increase. The pier avoids this and also avoids the necessity for the movable ground-level base that current elevator plans propose as a means of avoiding satellites.

The pier could be operated in virtually any weather.

The pier is designed to provide human access to space. A considerably shorter, high-acceleration version could be designed for robust freight. The elevator requires moving through the Van Allen belts at relatively low speeds, whereas the pier could launch through them at orbital speeds or avoid them altogether with polar trajectories.

The most significant advantages of the pier, however, are as a transportation mode: it has a significantly higher tonnage per annum capacity, and a significantly quicker time to orbit for any given payload.

3 Engineering

3.1 Structure and materials

Currently available polycrystalline diamond is advertised[4] as having a compressive strength of over 110 GPa (although its tensile strength is only 1.2 GPa). A square meter of such diamond would support a mass of 11 million tonnes. A one-square-meter column of diamond 11 million tonnes in mass would be over 3000 kilometers long. A column of diamond a mere 100 kilometers tall would be only 3% of the material's characteristic length in compression, and no taper would be necessary.

In other words, at if compressive strength is the limiting factor, the structural material of a 100 km tower need only be 3% of the total mass. If we can design a launch accelerator at one million tonnes (3.3 tonnes per meter of track), the diamond to support it would be only 32 thousand tonnes.

It will be difficult to design a structure with so little material that resists buckling and other lateral forces over 100 km of height and 300 km of length. Fractal openwork and inflated cylindrical shells are the techniques that appear to have the most promise. Even so, it may be best to consider the figure of 32,000 tonnes as a lower bound on the mass of the structure.

Polycrystalline diamond is like concrete (or sedimentary rock such as limestone) in having a much higher compressive than tensile strength. Western civilization has over 20 centuries of experience building quite impressive structures of such materials.

3.2 Footprint

In comparison to its total size, the footprint of the pier should be trivial. The total mass of the accelerator should be roughly comparable to that of the Golden Gate Bridge, largely supported by two towers whose bases are approximately an

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[4] http://www.sp3inc.com/diamond.htm

acre each. A nominal plan for the space pier is to have 62 one-acre footprints, spaced 10 km apart in two rows of 31.

3.3 Construction and maintenance

During construction, temporary bases for scaffolding and guy wires would be needed outside the footprints. For construction at higher altitudes, it is probably preferable to use teleoperated robots than attempt the construction with humans in spacesuits. Elevators inside the beams are feasible but would be quite time-consuming, and construction work in spacesuits is quite arduous.

Maintenance by telerobots is also indicated. Regular inspection, testing, and maintenance of the accelerator will be essential to reliable operation.

3.4 Accelerator

Several kinds of electromagnetic accelerator seem possible. Chief among them are coilgun mass drivers, linear induction motors, and synchronous linear permanent magnet motors. The latter is chosen for the reference design. With permanent magnets on the vehicle and passive coils, a proper arrangment (the Halbach-Post "inductrack"[5]) achieves a maglev effect powered only by the motion of the vehicle. This would form a valuable failsafe mode should sections of the track fail at the critical instant.

Powering the coils in an inductrack configuration would provide acceleration and the ability, if needed, to attract the craft to the track as well as repel it. Should this prove infeasible, a separate linear motor could be provided, perhaps with coils addressing both poles of permanent magnets mounted in a flange on the vehicle.

It is a prime design consideration that the launch vehicle be completely passive, even at some considerable expense in the design of the track. It is envisioned that the space pier will launch up to three times its own mass per year, and launch vehicle cost will form the greater part of the total. Thus economics clearly favors simplicity in the launch vehicle.

3.5 Power

The total kinetic energy in the launch vehicle exiting the pier is 300 GJ. The amount necessary to be supplied to the tower for the launch will be more, depending on the efficiency of the linear motor. Electric motors can attain over 90% efficiency, however, and thus it seems possible that inefficiency will not necessarily be a major item in the energy budget.

The pier might thus require the full ouput of two sizeable (1.5 GW) power plants to sustain a launch interval of 100 seconds. Alternatively, power satellites, launched by the tower in a bootstrap mode, could feed rectennas situated directly at the track–essentially space-to-space transmission, obviating many off the inefficiencies of ground-based rectennas.

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[5] http://www.llnl.gov/str/Post.html

Note that the energy per launch is constant per length of track, at 1 MJ per meter. An ordinary car battery holds well over 1 MJ, but is too slow to charge and discharge for the application. Steady-state power to the track is only 10 kW per meter, but the 1 MJ must be released, at the end of the track, in a millisecond (assuming a 10-meter vehicle).

The applicable technologies appear to be ultracapacitors or compulsators. Either technology appears capable of storing the requisite energy at 50-100 kg per meter of track.

A possible optimization would be to store energy in the magnetic fields of the coils of the track itself–an elegant solution which merits considerable further investigation.

3.6 Track distortions in Launch

Launch will subject the track to a rapidly-moving stress point of 1 MN axial, 100 kN lateral. This can be expected to set up substantial deflection and vibration in the track. Thus active damping will be necessary. Since the perturbing force can be predicted, control regimes not available to purely reactive systems can be used.

It is possible to design a track profile along which the launch would exert no lateral force. (This can be simply done by calculating the trajectory of a projectile in free fall decelerating at 10 G's along its instantaneous line of flight, and reversing it.) Since the track will be much more susceptible to lateral deflections than to axial ones, this may be a useful optimization. Note that the starting point of such a profile remains at 92 km altitude; there is no major reduction in either tower size or initial ascent time.

4 Operation

A typical launch would proceed as follows: The vehicle is placed on the vertical track at the ground base (western end) of the structure. It is boosted straight up at 1 G acceleration (2 G force) for 96 seconds, and then coasts for another 96 seconds to 92 km altitude.

Note that at 1 G acceleration the vehicle is 4.5 km up before going supersonic, minimizing noise impact on its surroundings. Even so, it would need to be faired. Some consideration needs to be given to the effects of supersonic operation in close proximity to the track at low altitudes. If necessary, lift profiles could be modified to hold ascent to subsonic speeds up to any desired altitude. Note that it would also be possible to enclose the ascent track up to, say, 15 km to shield it from weather and icing, and also to have separate tracks for faired (fast) and unfaired (slow) vehicles.

Once at the inflection point at the top of the ascent track, the vehicle is accelerated at 100 m/sˆ2 for 77 seconds. This puts it into a Hohmann transfer orbit with an apogee of 400 km. Circularization at 400 km requires a delta-V of 90 m/s, which could be done with 360 kg of solid fuel with a specific impulse of 250. (Again the design consideration is to keep the launch vehicle as simple as possible.)

Such a nominal launch profile places a 10-tonne vehicle in LEO with human-tolerable acceleration. Launching a lighter vehicle with higher acceleration could target the Moon at about 20 G's or HTO's for Mars or Venus at 22 G's.[6] (Of course completely different towers could be designed for those purposes, as well.)

5 Economics

If the tower can sustain a launch every 100 seconds, corresponding to a 3 GW power draw and a 23-second wait between track use (e.g. for self-test of the electronics, vibration damping, etc.), it can launch 3 million tonnes to orbit per year. For comparison, the New York City area airports handle a total of 2.5 million tonnes airfreight per year.

Estimating the cost of the tower is problematic since it involves attempting to harness economics of scale in as yet untested waters. The prime variable is cost of diamond. (Development of manufacturing methods for CVD diamond in large quantities can be amortized over a number of different applications.)

One very rough estimating method involves using price-per-mass of general classes of goods. The track, consisting of relatively conventional coils and electronics, can be estimated at $10/kg, and the diamond, assuming 3 times the minimum is actually needed, at $100/kg. This gives $10 billion for the track and another $10 billion for the structure. Add another $10 billion for everything else for a total of $30 billion.

To cover a 10% interest rate on the investment, the space pier must make $3 billion per year, or $1000 per tonne if it operates at full capacity. That's $1 per kilogram.

It is now clear why the engineering tradeoffs should emphasize simplicity in the launch vehicle. Even so, vehicle costs will predominate bare launch costs, especially for manned flights. Freight vehicles might drop below $1 per kg of payload if produced in quantity.

In the range of $1/kg to orbit, many applications become economical that currently are not. First is solar power satellites. In fact using space as a substitute for airfrieght is economical, although it would be limited to outgoing from the tower location until other towers were built. Business could locate high-prestige headquarters in orbit for less than they pay for some current locations. Passenger transport would likely be at rates affordable to the affluent and business travellers, but not to the general public.

A general LEO infrastructure would be feasible, with numerous permanent space stations. This would in turn enable interplanetary ventures (although those would, of course, be more expensive than LEO operations). The lunar mass driver scheme of O'Neill et al might well become economical, and in time, the orbital habitats as well.

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[6] see CRC Handbook, 52nd edition (1971) pp F-158-9, "Hohmann ellipse transfer data"