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DIVERSE CONFIGURATIONS OF THE SPACE CABLE

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The space cable is a development of the launch loop (or Lofstrom loop), which is held above the earth's surface by fast-moving bolts using magnetic levitation. Several configurations have been described that can be used for launching vehicles of up to 90 tonnes to space, either directly to orbit or, more economically, replacing a first-stage rocket. Several more configurations are now presented and costed. Some of them are capable of launching small vehicles directly to interplanetary space; others can be used for ramjets or scramjets. The space cable can also be used to support solar panels above the clouds, yielding between 2.5 and 4 times the power generated from similar panels on the ground in European countries. From this point of view, the power generated more or less pays for the space-launch infrastructure. The smallest application so far identified is a mobile rescue platform 300 metres high that could be used by fire departments. By exploring these diverse applications, it is hoped that the era of low-cost access to space will be brought closer.

I. INTRODUCTION

The space cable consists of several evacuated tubes standing on the ground or the sea and reaching to an altitude of up to 140 km. The tubes are held aloft by fast projectiles, called *bolts*, traveling inside them and using magnetic levitation. It is a development of the launch loop (or Lofstrom loop)[1] and is designed for launching vehicles into space using electromagnetic forces.

An advantage of the space cable is that smaller versions are possible for terrestrial applications, such as a mobile retractable ladder, which rises to 300 metres and is compact enough to be carried on a truck with a trailer. Such smaller-scale applications seem to offer a possible route by which the technology may be adopted. In addition, various configurations can offer different approaches to launching vehicles into space. For directly launching a manned vehicle to near-earth orbit, there is a version that extends over the ground for 1000 km. A smaller version is suitable for carrying an electric coil gun that can accelerate unmanned craft into orbit, or even directly to interplanetary space. This version rises to 50 km and extends over the ground for 115 km.

Another application of the space cable is to use it to support solar panels above the clouds, where the sunshine is consistent all day and the atmospheric filtering is small, obtaining much higher output than is possible on the ground in temperate climates. The advantage is so great that it pays for the whole cost of the space cable when compared with solar panels on the ground.

II. PREVIOUS WORK

The space elevator,[2] launch loop and space cable are all aimed at launching or assisting in launching vehicles to space at lower cost than using conventional rockets. In this way, we hope greatly to increase access to space, both for people and machines. The launch loop and space cable exploit magnetic levitation and linear drives using existing techniques and materials. The launch loop uses a continuous belt traveling at over 14 km/sec inside an evacuated sheath. It extends over 2000 km of the Earth's surface and rises to 80 km. It can launch manned or unmanned vehicles to near earth orbit by transferring energy and momentum to them electromagnetically from the traveling belt.

The space cable is a development of these principles in which the belt is replaced by separate bolts that are typically a metre long and separated by several metres. This allows greater flexibility: the bolts' spacing and speeds can be varied more widely than is possible with a belt. For example, a threefold reduction in the spacing between bolts is exploited during initial erection.[3] Bolts can be made in a factory by the thousand, and they can readily be replaced. Several pairs of tubes make up the space cable, and each tube has bolts traveling inside it; this allows one pair to be taken down for servicing while the others remain in place.

At each end of the space cable is a *surface station*, consisting of support tubes for steering and stabilization, a ramp for adjusting the angle of ascent or descent of the bolts, and an *ambit*, which is a circular tunnel or track that turns the bolts around so that they remain continuously in motion without losing significant kinetic energy.[4] Levitation at the surface stations uses superconducting magnets stabilized by electromagnets in the bolts. In the tubes, permanent magnets are used, and again electromagnets in the bolts provide stabilization. Each bolt contains electronic controls. The facility exists to perform regular diagnostic checks on the bolts and to replace any that appear to be performing outside specification. The other bolts can carry on unaffected.

A critical problem is to maintain stability in the presence of gusting winds, especially cross winds due to the jet stream. Early work suggested the need for a heavyweight solution involving a large support structure of tethers and stiffening elements.[5] Later, a far better solution was presented using a new technique called

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active curvature control.[6] The idea is to cause the space cable to bend to the right degree of curvature so as to counteract the wind force. The wind causes the space cable to bend in the right direction to oppose the force, but the bending is unstable. Electromagnets in each bolt apply small forces to correct the bending by interacting with the permanent magnets in the tubes. These same electromagnets are used for stabilizing the levitation forces that hold up the tubes, and so very little additional hardware is needed beyond some increased electronic sophistication.

Figure 1 Three versions of the space cable

Three illustrative examples have been described and costed.[7] Their shapes and sizes are shown in Figure 1. Versions 1 and 2 can replace the function of a first-stage rocket, which is the most costly part of the launch. Version 1 can accelerate a 90-tonne vehicle to 1.6 km/sec at 50 km height. Version 2 can deliver such a vehicle to 140 km height at 2.4 km/sec, from which a somewhat smaller rocket can complete the launch of a substantial payload to orbit. Version 3 can deliver manned vehicles directly to orbit. Approaching the launch loop in size, it extends over 1000 km of the Earth's surface. The acceleration in these versions is up to 6*g*, i.e., six times the acceleration due to gravity, which is suitable for manned vehicles. The height of version 3 is also 140 km. That height is close to the practical ceiling for this technology. Above about 140 km, the mass of material needed at the top to support the lower levels becomes much greater, due to the exponential nature of the equation,[4] assuming the use of Kevlar® with a safety margin of four to one. This height limit has the advantage that it largely avoids the problem of space debris.

Using momentum transfer from the bolts, the practical speed limit is about 75% of the bolt speed. With a bolt speed of 10.9 km/sec, version 3 can launch a 60-tonne manned vehicle to 7.9 km/sec, just enough to reach near-earth orbit. Ion or other engines can then be used to propel such a vehicle on a variety of different missions to geosynchronous orbit, to the moon and to interplanetary space at a fraction of the cost of launch by chemical rockets.

Version 1 is estimated to cost $2.4 billion, version 2 is $7.4 billion, and version 3 is $25 billion.[7] Since one of the objectives of work on the space cable is to lower costs, the smaller versions seem preferable. So far, they have been limited in one aspect of their design, namely, that the ultimate velocity of the vehicle is less than the velocity of the bolts from which they draw both energy and momentum as they travel.

III. ELECTRIC COIL GUN

To achieve launch velocities higher than the velocity of the bolts, a design is proposed based on the electric coil gun.[8] Electromagnetic coils are placed along the space cable, and they draw power from supercapacitors. The main advantage over existing designs of electric gun is the high altitude, greatly lowering losses due to air resistance. Another advantage is that the gun can be very long, permitting a relatively high launch mass with relatively low acceleration. Electric guns often deliver accelerations in excess of 1000*g*, which are tolerable for unmanned vehicles. Direct launch to orbit, or even to interplanetary space, is feasible. A design is presented below that can launch 100 kg at 10 km/sec with an acceleration of 100*g*. It can also launch 60 kg at 15 km/sec with an acceleration of 150*g* using the same cradle. At 15 km/sec, a payload has enough kinetic energy to leave Earth's gravity well with a residual speed of 10 km/sec. (Earth's escape velocity V is 11.2 km/sec, kinetic energy is $\frac{1}{2}MV^2$ for mass M, and $\frac{1}{2}M(15^2-11.2^2)\approx\frac{1}{2}M10^2$.) Accelerations of 100*g* to 150*g* widen the usefulness of the launcher compared with thousands of *g*; payloads do not have to be quite so robust.

The launch vehicle is carried on a cradle, consisting of support struts pulled by a line of permanent magnets. They are bound with Kevlar (for tensile strength) and reinforced carbon-carbon (RCC). RCC is the material used as a heat shield on the nose cone and leading wing edges of the space shuttle; it also serves as a structural element to maintain the desired shape. Both these capabilities are used in the space-cable electric gun.

For efficiency and to avoid overheating, the coils are energized only when the launch vehicle and cradle are near. Effectively, they create a traveling electromagnetic wave along the space cable. Although plenty of energy is available from the bolts, the coils needed to extract the power (i.e., energy per unit time) would be too heavy. It is better to store the required energy in supercapacitors distributed along the gun. The thrust is transmitted through the tubes to the opposite surface station as tension. It represents only about 5% of the tension already present in the tubes, and the bolts can readily sustain it.

The distribution of supercapacitors is uniform along the gun, because the energy requirement per unit distance is constant, even though the power requirement goes up with the speed of the payload. The supercapacitors must discharge while the payload is in their section of the gun. This means they must discharge faster where the payload speed is greater.

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The power required for a mass M at velocity V is the rate of change of kinetic energy:

$$\frac{d}{dt}\left(\tfrac{1}{2}MV^2\right) = MV\frac{dV}{dt} \quad (1)$$

Hence the energy required per unit distance is equal to the thrust and is simply:

$$E_d = M\frac{dV}{dt} \quad (2)$$

The cradle supports the weight of the payload and maintains stability using magnetic levitation with the bolts, much like the bearer in versions 1-3.[4] At high speeds, rather than supporting the weight, the cradle has to hold the payload down until its release. The cradle's mass is estimated at about 20 kg.

The acceleration a required to reach speed V over distance d is given by $a = V^2/2d$. To achieve a launch speed of 10 km/sec over a distance (the *runway*) of 50 km therefore needs an acceleration of 10^3 metres/sec^2, just over 100g. A mass of 120 kg (launch vehicle plus cradle) needs a thrust of 120 kN. This thrust is transmitted in the form of tension through the space cable to the opposite surface station.

The energy required per metre (equation (2)) is 1.2×10^5 joules, which is about 33 Wh (Watt-hours). Assuming 50% efficiency in the coils, the energy storage needed is 66 Wh. With supercapacitors, the weight is about 2 kg per metre. The preferred method of recharging the supercapacitors is to use solar panels. As explained in section V, a one-square-metre panel delivers 180 watts throughout the day and weighs 1 kg. One of these per metre will recharge the supercapacitors in 22 minutes. Recent laboratory advances in nanocapacitors have demonstrated an energy density as high as 3 kWh per kg,[9] two orders of magnitude improvement over supercapacitors. Depending on costs, they could enable much higher payloads to be launched in this way.

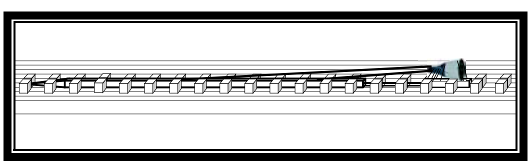

Figure 2 Cradle on space cable with payload

Using the tool *Finite Element Method Magnetics (FEMM) 4.2*, an arrangement has been modeled that gives a thrust of 7500 N from a pair of electromagnets with a mass of 2.35 kg. 16 such pairs will therefore give the desired thrust of 120 kN. This is achieved on a line of Neodymium Iron Boron (NIB) permanent magnets of cross section 1 cm by 1 cm. The length is 16 metres, so that one pair of electromagnets is needed per metre on the space cable. Figure 2 shows pairs of electromagnets placed along the space cable with the cradle passing between them hauling the payload. Each pair of electromagnets weighs 2.35 kg per metre to which must be added the supercapacitors, the solar panels and some control electronics, giving a total weight estimate of 6 kg per metre.

The line of NIB magnets has a volume of 1.6×10^{-3} metres^3 and a mass of 12.5 kg. The tensile strength of Kevlar is rated at 3.6 GigaPascal, but a 4:1 safety margin leads us to assume a strength of 9×10^8 Pascal. Therefore, the cross section is 1.33×10^{-4} metres^2. The full length is 21 metres (Figure 2) to minimize the torsion effect, giving a mass of 4.1 kg. A similar volume of RCC is needed, giving a mass of 5.6 kg. This sums to a cradle mass of 21 kg.

A space cable reaching an altitude of 50 km and covering a range over the ground of 108 km is suitable for carrying this electric gun. (This and similar calculations are done using a computer model based on the mathematics published in ref. 3.) It is similar to version 1 (see section II), but with the additional 6 kg weight per metre. There are 10 tubes, but it is desirable to share the weight among eight tubes in case it is necessary to remove one pair from service for maintenance. The weight then amounts to 0.75 kg per metre per tube. This, combined with the additional tension, makes a moderate but noticeable difference to the mass of supporting Kevlar needed in their construction and to other statistics. The 10 tubes are each 145 km long. The maximum levitation force between tube and bolt is at the top and is 600 N, which means each tube needs 0.5 kg per metre of NIB permanent magnets incorporated into its construction. The bolt speed v is 2.0 km/sec at the surface. Their mass m is 7 kg, and they are spaced at 5-metre intervals. Thus 290,000 bolts are required for ten tubes. The ambit radius R is given by the formula $R = mv^2/F$, where the force F between bolts and superconducting magnets is about 190 kN. Thus the radius is 147 metres, giving a total length of ramp plus ambit of $12\times147 = 1764$ metres, about 3.5 km over the two surface stations.

<u>Costs</u>

The estimates are based on retail prices to allow for construction. NIB costs about $250 per kg, giving a cost per metre per tube of $125, to which we add $50 per metre for other materials such as expansion joints and vacuum-tight materials. This gives a cost estimate for ten tubes of about $255 million. To this we add the mass of Kevlar, which is 348 tonnes per tube, costed at $90,000 per tonne, giving a total over 10 tubes of $315 million. There are 46 support tubes at each station, costing $100 million in total.

Previous estimates for versions 1-3 show the bolts costing $580 each, but they are designed to provide thrust to heavier vehicles such as upper-stage rockets. Some savings could be made if such launches are not

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required, but it seems more desirable to keep this capability. The cost of 290,000 bolts then comes to about $170 million.

The surface station costs are based on figures of $93 million per km from CERN in Geneva, giving $325 million for 3.5 km over the two surface stations.

For the electric gun, a pair of coils is needed per metre, costed at $450 a pair. Over the 50-km runway, this comes to $22.5 million. Further coils are needed to slow down the cradle after the vehicle has been launched. When the terminal velocity is 15 km/sec, the cradle accounts for 25% of the overall 80 kg mass, and so an additional 25% is needed, bringing the cost of coils to $28 million. On the runway, 66 Wh of supercapacitor storage per metre is required, costed at $460 per Wh. These amount to $30,400 per metre over 50 km, giving a total of $1520 million. A few supercapacitors are needed for decelerating the cradle to absorb some of the energy acquired. In effect, this is electro-regenerative braking, and the energy can be used to return the cradle slowly to its starting place. Because of losses, an additional 5% of supercapacitors are sufficient, amounting to $76 million. These three figures total $1624 million.

The sum is $3.5 billion, including 20% R&D.

	US$ millions
Tubes	250
Kevlar	315
Support tubes	100
Bolts	170
Surface stations	325
Electric gun	1624
Solar panels	110
Subtotal	**2894**
R&D 20%	579
TOTAL	**3473**

IV. SMALLER ELECTRIC COIL GUN

A smaller version rising to only 15 km has been considered. The tube length is 45 km, and it covers a range over the ground of 30 km. Arguably, the launch vehicle needs to reach a higher velocity (about 11 km/sec) to overcome the additional atmospheric friction at the lower altitude and still attain 10 km/sec by the time it reaches 50 km. To achieve 11 km/sec velocity over a 20 km runway requires an acceleration of 3×10^3 metres/sec^2, nearly 310g. Assuming the same thrust of 120 kN, the mass (launch vehicle plus cradle) is limited to 40 kg. Keeping the same design of cradle leaves 20 kg for the launch vehicle.

The thrust and energy storage E_d (equation (2)) required per metre are the same as for the larger electric gun at 66 Wh, since the mass has been reduced as the reciprocal of the acceleration. Solar panels are less attractive because of the problem of jetstream winds, which would exert forces difficult to manage using active curvature control (see section II). The total energy required to recharge the supercapacitors after a launch is 1320 kWh. A 4 MW generator can recharge them in 20 minutes.

The maximum levitation force between tube and bolt is 360 N, which means each tube needs 0.3 kg per metre of NIB permanent magnets incorporated into its construction. The bolt speed v is 1.1 km/sec at the surface. Their mass m is 4 kg, and they are spaced at 4-metre intervals. Thus 113,000 bolts are required for 10 tubes. The bolts are lighter because they are relatively short; they are 60 cm long instead of 1 metre so that they will fit in the smaller ambit radius. However, they still need more or less the same capabilities and will cost the same.

The ambit radius is 26 metres, giving a total length of ramp plus ambit of about 625 metres over the two surface stations.

Costs

The tube costs are about $135 per metre, giving a cost estimate for ten tubes of about $61 million. To this we add the mass of Kevlar, which is 31 tonnes per tube, giving a cost over 10 tubes of $28 million. The support tubes' cost is about $20 million. 113,000 bolts come to about $66 million. The two surface stations together cost $60 million for 620 metres.

Over the 20-km runway, a pair of coils per metre costs $9 million. The cradle accounts for 50% of the overall 40 kg mass, and so an additional $4.5 million is needed for the coils that slow the cradle down after the launch. 66 Wh of supercapacitor storage per metre costs $30,400, summing to $608 million over 20 km. Another 12.5% is needed for electro-regenerative braking costing $76 million. The sum is $698 million.

These figures sum to $1.1 billion, including 20% R&D.

	US$ millions
Tubes	61
Kevlar	28
Support tubes	20
Bolts	66
Surface stations	60
Electric gun	698
Subtotal	**933**
R&D 20%	187
TOTAL	**1120**

V. SOLAR POWER GENERATOR

The space cable can be used to hold photo-voltaic cells above the cover of clouds so that solar power can be generated in cloudy regions of the world far more efficiently than on the ground. In work using balloons, it has been calculated that more than four times the influx

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of solar power can be obtained above an altitude of about 7 km compared with ground level in England.[10] The equivalent factor in southern Spain is about 2.5. Both figures include a factor of 30% because of the reduced atmospheric filtering. Assuming a typical figure of 15% efficiency for a photo-voltaic array, an output of 180 W/metre^2 can be expected throughout the day. The weight is about 1 kg/metre^2.

An attractive option is to build a multi-purpose structure that can be used for solar panels in addition to launching space vehicles, providing rides for tourists and supporting platforms for science and communications. This structure is based on version 1 of the space cable (see section II), which can be used to replace a first-stage rocket for launching 90 tonne vehicles to 1.6 km/sec.

To yield a useful amount of power, several square metres of panels per metre length of cable are needed. It is desirable to place the solar panels above the jetstream zone to avoid strong lateral forces. Version 1 rises to 50 km, and 150 km of its length is above 12 km altitude. Suspending 20 kg of solar panels per metre adds 2.5 kg per metre to the weight of each tube, allowing for one of the five pairs of tubes to be out of service. 20 kg amounts to 20 metre^2 and yields 3.6 kW. Hence the yield over 150 km is 540 MW. Because this output can be obtained throughout the day almost every day of the year, the annual output is 2200 GWh. The same solar panels on the ground in England would yield about 500 GWh per year. In southern Spain, the yield would be about 900 GWh per year.

To transmit the power to the ground, the panels can be connected in a combination of series and parallel in order to optimize the weight without excessive losses. An aluminum conductor of 6 mm radius has a cross section of 1.1 cm^2 and therefore a resistance per metre of 2.5×10^{-4} ohms, based on a resistivity of 2.8×10^{-8}. Over the cable length of 188 km, this comes to 46 ohms. The weight per metre is 0.3 kg, which is already factored in to the weight estimates of the solar panels. If we tolerate a loss of 1 MW, we can allow a current of 150 amps. Then the potential difference between the two surface stations is found by dividing the power by the current and is 3.6 MV (million volts). At each station, the potential difference with the ground is half this at 1.8 MV, needing an insulation thickness of 2 mm of a Polyurethane conformal coating. Therefore, the cross section of the insulator round the 6 mm radius conductor is $\pi 10^{-6}(8^2-6^2)\approx 8.8\times10^{-5}$ metre^2, or 88 mm^2; the weight is negligible.

Costs

The extra weight entails additional cost to cope with the increased levitation forces in the tubes (from 305 N to 580 N). The cost of NIB magnets rises from $85 to $130 per metre per tube, giving a tube cost of $180 per metre. The amount of Kevlar per tube is 610,000 kg instead of 410,000 kg. The maximum bolt speed is 2.5 km/sec, increasing the surface-station costs from $470 to $575 million. The bolt spacing has been reduced from 5 metres to 4, adding 25% to their number. Whereas version 1 has a cost estimate of $2.4 billion, the costs to support the solar panels add about 20%, making $2.9 billion.

	US$ millions
Tubes	340
Kevlar	550
Support tubes	100
Bolts	275
Surface stations	575
Bearer and vehicles	600
Subtotal	**2440**
R&D 20%	488
TOTAL	**2928**

The estimate for the photo-voltaic cells is $4 per Watt,[10] giving a total of $2.2 billion. The combined cost is therefore $5.1 billion. Ground-based solar panels to supply equivalent output in England would come to $8.8 billion, and so the space cable yields a substantial net saving. In southern Spain the equivalent cost drops to $5.5 billion, so there is still a net saving. Viewed in this light, the other uses of the space cable are essentially free.

VI. LARGER ELECTRIC COIL GUN WITH SOLAR POWER GENERATOR

A coil gun 250 km long can be placed on a version of the space cable that is intermediate between versions 2 and 3 (see section II). To attain 10 km/sec requires an acceleration of 200 metres/sec^2, about 20*g*, 15 km/sec requires 450 metres/sec^2, and 30 km/sec requires 1800 metres/sec^2. Assuming the same thrust of 120 kN, as in the smaller versions, the respective masses (launch vehicle plus cradle) are 600 kg, 260 kg and 66 kg. A somewhat larger cradle is needed to carry the greater weights, but the thrust is the same. For the 66 kg, extra heat shielding is needed. In both cases, the cradle mass is estimated at 30 kg, leaving 570 kg, 230 kg or 36 kg for the respective launch vehicle.

Assuming it is possible to cope with the atmospheric friction at such a speed, 30 km/sec is enough for a direct launch to Mars. After subtracting the energy lost escaping from Earth ($\frac{1}{2}MV^2$ with $V=11.2$, the escape velocity) and getting further from the sun ($\frac{1}{2}M(42.1^2-34.1^2)$ based on the solar escape velocities at Earth and Mars), the remaining speed is 12.8 km/sec. This enables the journey of 100 million km (depending on orbital alignment) to be completed in about three months.

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The thrust and energy storage E_d (equation (2)) required per metre is the same as for the other versions at 66 Wh, allowing for 50% efficiency.

Combining the coil gun with a solar power generator means that the supercapacitors can be recharged in only 66 seconds if desired. At other times, there is a net power output of 3.6 kW per metre extending over 500 km to produce 1.8 GW throughout the day every day, an annual output of 7200 GWh.

The maximum levitation force between tube and bolt is 1300 N, which means each tube needs 1.1 kg per metre of NIB permanent magnets incorporated into its construction. The bolt speed v is 5 km/sec at the surface. Their mass m is 7 kg, and they are spaced at 2-metre intervals. The tube length is 500 km. Thus 2,500,000 bolts are required for 10 tubes.

The ambit radius is 920 metres, giving a total length of ramp plus ambit of 22 km over the two surface stations.

Costs

The tube costs are about $325 per metre, giving a cost estimate for ten tubes of about $1.6 billion. To this we add the mass of Kevlar, which is 10,000 tonnes per tube, giving a cost over 10 tubes of $9 billion. The support tubes' cost is $100 million. 250,000 bolts come to about $1.5 billion. The two surface stations together cost $2 billion for 22 km.

The electric gun is five times the length of the first version, and so the coils and supercapacitors on the runway are five times the cost at $112.5 million and $7.6 billion respectively. The cradle accounts for 45% of the mass in the most extreme case, so 45% more of the coils and 11% more of the supercapacitors are needed for deceleration, which comes to $51 million and $836 million respectively. The total is $8.6 billion.

These figures sum to $27 billion, including 20% R&D.

	US$ millions
Tubes	1600
Kevlar	9000
Support tubes	100
Bolts	1500
Surface stations	2000
Electric gun	8600
Subtotal	**22800**
R&D 20%	4560
TOTAL	**27360**

The estimate for the photo-voltaic cells at $4 per Watt is $7.2 billion. The combined cost is therefore $34.2 billion. Ground-based solar panels to supply equivalent output in southern Spain would come to $18 billion, substantially reducing the net cost of this launcher. In England the equivalent cost is $28.8 billion, leaving a relatively small net cost when considered on this basis.

VII. SCRAMJET OR RAMJET BOOSTER

The speed of commercial aircraft has been limited largely by the sound barrier. Ramjets and scramjets have been known for decades, but they have not been successfully commercialized. There have been studies into using scramjets for launching into space.[11] A ramjet is suitable for speeds between Mach 2 and 6 (about 0.6 to 1.8 km/sec), while a scramjet operates above Mach 5, in the so-called hypersonic range. A limiting factor in their adoption has been the need for another form of propulsion to accelerate them to their operating speeds. The space cable can perform this role, greatly simplifying the design of a supersonic or hypersonic aircraft and saving valuable weight and fuel.

The space cable also helps to overcome other inhibitory factors:

- Research is needed into the problem of sonic boom. It is thought that careful wing and airframe design can mitigate boom, but testing is difficult. The space cable can be used as a platform for research, development and testing of suitable components without the need to assemble a complete flying ensemble. Repeated journeys can be arranged easily at moderate expense.
- An engine test facility can be carried on the space cable. Ground testing of scramjets is particularly problematic, and aerial testing involves complex and expensive use of rockets and other facilities. By contrast, the space cable can carry an engine with a test bed for repeated journeys.

Version 1 (height 50 km, length 188 km) can provide a thrust of 4.5 MN with a 15-tonne bearer. Therefore, a combined engine and test facility of 25 tonnes can be accelerated at 110 metres/sec over 12 km. It can then run for about 100 seconds at 1.6 km/sec (just over Mach 5) at altitudes between 10 and 50 km before being decelerated. In the same way, wings and other components can be tested. Other versions can be used for greater altitudes and speeds.

For space launch, ramjets or scramjets offer the prospect of providing a cost-effective first stage in a two-stage vehicle. The air-breathing stage is intended to return to ground and be reused. The rocket stage completes the lift to orbit. The space cable is suitable both as a test bed and for deployment of such air-breathing technology.

A commercial airliner using ramjets would be able to slash journey times to a third or less of those achieved today. Acceleration would have to be limited to 5 metres/sec^2 (0.5g) to accommodate general passengers. Reaching Mach 2 then takes 36 km. A space cable 20 km high is adequate for this task, with a tube length of 70 km and a bolt speed of 1.2 km/sec. The aircraft is

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launched at 1350 mph and an altitude of 65,000 feet, which is 15,000 feet higher than Concorde's cruising altitude.

The bolt mass *m* is 4 kg, and they are spaced at 4-metre intervals. The maximum levitation force between tube and bolt is 175 N, which means each tube needs 0.2 kg per metre of NIB permanent magnets incorporated into its construction. The bolt mass *m* is 4 kg, and they are spaced at 4-metre intervals. Thus 175,000 bolts are required for 10 tubes. The ambit radius is 30 metres, giving a total length of ramp plus ambit of about 720 metres over the two surface stations.

Costs of ramjet booster

The tube costs are about $100 per metre, giving a cost estimate for ten tubes of about $70 million. To this we add the mass of Kevlar, which is 33 tonnes per tube, giving a cost over 10 tubes of $30 million. The support tubes' cost is about $20 million. 175,000 bolts come to about $100 million. The two surface stations together cost $67 million for 720 metres. The bearer costs $200 million.

These figures sum to $580 million, including 20% R&D.

	US$ millions
Tubes	70
Kevlar	30
Support tubes	20
Bolts	100
Surface stations	67
Bearer	200
Subtotal	**487**
R&D 20%	97
TOTAL	**584**

To give this figure a context, Terminal 5 at London Heathrow Airport opened in 2008 at a cost of $6.7 billion (£4.3 billion). Of course, a ramjet booster would need to be installed at both ends of the route for return flights. A long, dedicated runway on the ground would be required for glide landings.

VIII. LADDER OR RESCUE PLATFORM

One of the challenges in finding small-scale applications of the space-cable technology is that there are more conventional solutions to most small-scale problems that it can solve. The smallest application devised so far is a portable ladder for emergency use, for example in accessing tall buildings.

The ladder rises to 300 metres (1000 feet) and can be deployed on a truck with a trailer. This is well beyond the current capability of fire-department ladders.*

* Typical ladders for sale reach to 125 feet: see e.g., http://www.smeal.com/apparatuscategory.aspx?type=2

One or more platforms can be raised to the top and lowered again to carry people, equipment or goods. The ladder is designed to tolerate a load of 30 kg per metre, so the weight of a 1-tonne platform must be distributed over 33 metres.

The ladder has one pair of tubes, and each is 635 metres long. The role of the surface stations is now taken by two drums, one on the truck and the other on the trailer. The drums contain superconducting magnets for turning the traveling bolts around. When deployed, the bolts ascend and descend inside the tubes. When a bolt arrives at a drum, it passes inside it, where it is turned around to emerge through the other tube, just as in the ambit. Thus each drum has a pair of tubes attached (Figure 3). The drums are shielded to reduce magnetic leakage (not shown).

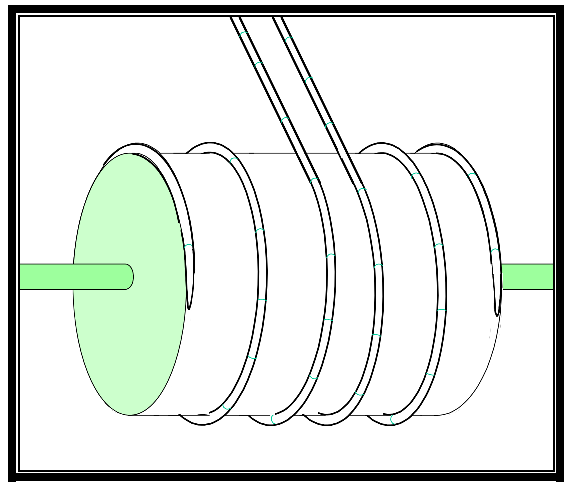

Figure 3 Arrangement of the tube round a drum

To stow the ladder, the tubes are wound round the drums. When stowed, half of each tube is on each drum, leaving a short length of each tube between the truck and trailer. During operation, the superconducting magnets inside each drum exert a centripetal force that causes the bolts to travel round and round the drum while remaining in the tubes.

The first step in deploying the ladder is to accelerate the bolts inside the tubes so that they start to travel round and round the drum, passing from one drum to the other and back again, until they reach the necessary speed. Then the tubes are unwound from the drums. The angle at which the tubes emerge from the drums causes them to rise as the drums are unwound.

Whereas larger versions of the space cable have fairly long ranges over the ground, a short range is needed to make the ladder usable in confined spaces. We do not want to have to separate the truck and trailer by 75 or 100 metres. However, we need a relatively flat section of the tubes at the top so as to spread the weight that the permanent-magnet levitation imposes on the

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passing bolts. To achieve both objectives, we add cross bracing (Figure 4) that draws the tubes together at the lower elevations while leaving them more widely separated higher up. A crawler mechanism keeps this bracing tidy and avoids snagging during erection and retraction.

The drums' radius is 1.5 metres. 68 turns are needed to fit 635 metres of tube with a diameter of 5 cm, and so the drums' width is 3.4 metres. To pass round the drums without colliding with it, the bolts are only 10 cm long and have a mass of 1 kg. They are spaced at 50 cm intervals and travel at 186 metres/sec. The tubes are 635 metres long, and so 2540 bolts are required for two tubes. An external load of up to 30 kg per metre is distributed between the two tubes, and this leads to a maximum force between tube and bolt of 1500 N, which means each tube needs 1.5 kg per metre of NIB permanent magnets incorporated into its construction. The total mass of NIB is 1805 kg. About 80 kg of Kevlar is needed.

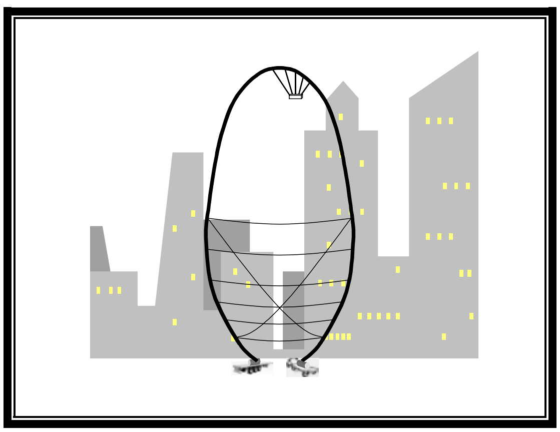

Figure 4 Cross bracing for a more convenient shape

<u>Costs</u>

In the tables, the costs are now in thousands rather than millions. The tube costs are about $425 per metre, giving a cost estimate for two tubes of $544,000. 80 kg of Kevlar costs $7200. 2540 bolts come to about $1.5 million. Each drum has a circumference of almost 10 metres; using the same formula as for the surface stations gives a cost estimate of $1.9 million. The cradle is taken at $50,000.

These figures sum to $4.8 million, including 20% R&D but not counting the truck and trailer.

	US$ thousands
Tubes	544
Kevlar	7
Bolts	1500
Drums	1900
Cradle	50
Subtotal	**4001**
R&D 20%	800
TOTAL	**4801**

IX. CONCLUSION

Versions 1-3 can all launch quite large vehicles, between 60 and 90 tonnes. Of these, version 1 is probably the most cost effective because it replaces the heavy lifting stage of launch by rocket. It is well suited to generating power from photo-voltaic cells and is more economical than generating the equivalent power from photo-voltaic cells on the ground, whether in a good site in southern Spain or a poorer site in England. It is also good for scramjet testing. A 20-km high version is suitable for commercial ramjet airliners.

It is possible to launch vehicles electromagnetically direct to space using an electric coil gun, but the capital cost is significantly higher and the vehicle sizes are much smaller – up to half a tonne. This is because the method of momentum transfer used in versions 1-3 is not able to accelerate vehicles above about 75% of the bolt velocity. In versions 1-3, a 20-tonne bearer 150 metres long extracts both energy and momentum from the bolts using electromagnetic coils which move with the vehicle. In an electric coil gun, the energy is stored in supercapacitors along the space cable and then used to power the coils (of moderate mass) that provide thrust to the launch vehicle via a relatively small cradle with a mass of 20-30 kg. The supercapacitors constitute the major cost factor.

Many other combinations of sizes and features are possible. The examples have been chosen as fairly representative of what is possible for launch to space and other applications. Tourism offering a gentle ride to the top of the cable is likely to be an attractive offering. Scientific uses are also promising, such as an observatory that has most of the benefits of a space telescope but is still accessible for servicing and upgrade.

The space-cable technology may have a better chance of being adopted for a smaller-scale application that requires a smaller investment. To this end the 300-metre (1000 feet) ladder or rescue platform is proposed with a cost estimate in the low millions rather than billions. The key feature is the ability to roll up the structure round a pair of drums. Even smaller applications are feasible, but they are only of interest as proofs of concept, since there are probably cheaper, more conventional, solutions already available.

Applications rejected as feasible but too costly include high-altitude wind farms and very wide-span bridges (e.g., for crossing the English Channel). However, high-altitude solar panels supported by the space cable appear to be cost effective.

All the configurations mentioned here can be built with known materials that are commercially available. The technologies used are moderate extensions of what

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is working today. The exploration of small-scale applications brings us closer to realizing the objective of low-cost, low-energy access to space for humanity.

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