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THE SPACE ELEVATOR: 'THOUGHT EXPERIMENT', OR KEY TO THE UNIVERSE?

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DEPLOYING THE CABLE

The space elevator may be regarded as a kind of bridge, and many bridges begin with the establishment of a light initial cable -- sometimes, indeed, no more than a string towed across a canyon by a kite. It seems likely that the space elevator will start in the same way with the laying of a cable between geo stationary orbit and the point on the equator immediately below.

This operation is not as simple as it sounds, because of the varying forces and velocities involved, not to mention the matter of air resistance after atmospheric entry. But there are two existing technologies which may provide a few answers, or at least hints at them.

The first is that of submarine cable laying, now considerably more than a century old. Perhaps one day we may see in space something analogous to the triumphs and disasters of the *Great Eastern,* which laid the first successful transatlantic telegraph cable -- the Apollo Project of its age.

But a much closer parallel, both in time and sophistication, lies in the development of wire-guided missiles. These lethal insects can spin out their metallic gossamer at several hundred kilometres an hour. They may provide the prototype of the vehicle that lays a thread from stationary orbit down to earth.

Imagine a spool, or bobbin, carrying some 40000 km of filament, a few tenths of a millimetre thick at the outer layers, and tapering down to a tenth of this at the core -- the end that finally reaches Earth. Its mass would be a few tons, and the problem would be to play it out evenly at an average velocity of a kilometre a second along the desired trajectory. Moreover, an equivalent mass has to be sent outwards at the same time, to ensure that the system remains in balance at the stationary orbit.

My friend Professor Ruppehas investigated [12] the dynamics of the mission, and concludes that it can be achieved with modest mass-ratios. But the mechanical difficulties would obviously be formidable, and it may well turn out that material of such tensile strength is too stiff to be wound on to a spool of reasonable radius.

Sheffield [18] has suggested an alternative method of installation which I find -- to say the least -- hair raisingly implausible. He proposes constructing the entire space elevator system in orbit, and then launching it towards the earth, grabbing the lower end when it reaches the equator! The atmospheric entry of a few megatons dead weight, which must impact within metres of the aiming point, seems likely to generate a lot of opposition from the environmentalists. I call it 'harpooning the Earth', and would prefer not to be near one of the Poles if it's ever tried out.

THE MASS ANCHOR

In order to balance the weight of the lower portion, and to compensate for the reaction produced by ascending payloads, the space elevator has to extend far beyond geostationary orbit. The upper portion may be regarded as the mass which keeps the cosmic sling taut, as it whirls round the Earth every 24 h.

This mass could be provided by another tapered cable, extending out into space, but it has to be very much longer than the lower portion to produce equilibrium. Indeed, calculations show that it must reach the enormous height of 144,000 km. I do not think that a cosmic flail extending a third of the way to the moon will make the Earth a nice place to visit.

The alternative is to have a large mass anchored at a much lower altitude, not far above the geostationary orbit. The closer it is, the larger the mass required; it might be many megatons, or even gigatons. Both Sheffield and I have suggested that captured asteroids could be used for this purpose, and as many of them now appear to be largely carbonaceous they could also supply much of the material of the elevator, the remaining *debris* providing the anchor.

CATASTROPHES

A structure extending right through the atmosphere and on into space for at least 50000 km would be a considerable navigational hazard, both to aircraft and spacecraft. Very elaborate anti-collision measures would have to be taken and all air traffic would have to be diverted from the equatorial danger zone. Probably the structure would be strong enough to survive impacts at atmospheric velocities; *cosmic* speeds would be another matter.

The problem here is aggravated by the fact that, over a long enough period of time, *all* satellites with perigees below geostationary altitude would eventually collide with the space elevator, as their orbits precess around the earth. So before the elevator is built, there would have to be a thorough job of garbage collection, and thereafter all remaining satellites would have to be closely watched. Whenever they approached too near the elevator, they would have to be nudged into a safer orbit. The impulses required would be trivial, and need be applied only very infrequently.

Meteorites present a more difficult problem, since they would not be predictable. But the impact of a large one would be a very rare occurrence indeed, and the elevator would have to be designed with enough redundancy to withstand any reasonable danger. Thus if it was in the form of an open framework -- like a boxgirder -- a meteorite should be able to pass through it in any direction without causing a structural failure.

But what if the elevator *is* severed? -- Well, if the elevator is cut through at the Earth's surface, it would de exactly the opposite of a terrestrial building. It wouldn't fall down -- but would rise up into the sky! In theory, the loose end might be secured and fastened down again; but that would be, to say the least, a tricky operation. It might even be easier to build a new system....

If the break occurred at any altitude up to about 25000 km, the lower portion of the elevator would descend to Earth and drape itself along the equator while the now unbalanced upper portion would rise to a higher orbit.

Hopefully, such major catastrophes can be avoided by good design; after all, it is very rare indeed for a modern bridge to collapse. (Though it *has* happened!) Much more likely -- indeed, inevitable -- is that objects would accidentally fall off the elevator. Their subsequent fate would depend upon their initial altitude

The situation here is totally different from that encountered in orbital flight. If you step outside a Spacecraft, you stay with it. But if you step off the elevator' it's rather like jumping out the window on the thousandth -- or ten thousandth -- floor of a rather tall skyscraper. Even so, you might still be quite safe because you wouldn't fall vertically. You would share the structure's horizontal velocity as it whirls round with the spinning Earth; in other words, you would be injected into an elliptical orbit.

If your initial height is less than 23000km, too bad. Your orbit will intersect the atmosphere in a few hours -- or even minutes - - and you'll burn up on the other side of the planet. Above this critical altitude, you would be in a stable orbit, skimming the atmosphere and coming back, after one revolution, to the place you started from. Of course, by then the elevator would be somewhere else, but with luck your friends might be waiting for you with a net and some well-chosen words of advice. Or if not on *this*revolution, on a subsequent one....

If you stepped off at the geostationary altitude itself, here, and only here, you would remain with the elevator, just as in conventional orbital flight. At higher altitudes, you would be injected into orbits of increasing eccentricity, with periods of one day and upwards.

That is, until you reached *another* critical altitude -- 47000 km. At this point, you'd be slung off into space at more than the local escape velocity, and would never return. You would become an independent planet of the Sun, and it might not be possible, owing to budgetary considerations, to rescue you and bring you back to Earth.

The analogy with a sling is now complete. Payloads released anywhere above the 47000 km altitude would escape from the Earth's gravitational field, and by going to greater and greater altitudes any desired launch speed could be attained. Pearson [9] has shown that *all* the planets can be reached by this technique, without the use of any other propulsion. The energy comes, of course, from the rotation of the Earth.

BEYOND THE EARTH

The lower the gravitational field of a planet, and the quicker its speed of rotation, the easier it is to build a space elevator. On a small asteroid the feat would be absurdly simple, and could even be achieved by a free-standing tower. There would be no need for suspended cables made of exotic materials.

Pearson [9] has pointed out the advantages of *lunar*Space elevators -- in this case, linking the Moon's equator with the well-known Lagrangian points in the line joining Earth and Moon. He calls them 'anchored lunar satellites', and they could be constructed of materials already available. Working in conjunction with the earth-based elevator, they would permit two-way traffic between Earth and Moon with almost zero use of rocket propellants.

The planet which seems ideally suited for the space elevator is Mars, with only one third of Earth's gravity. What is more, the outer satellite Deimos is only slightly above stationary orbit -- in just the right position to provide a mass anchor! Moreover, it appears to be largely carbonaceous, so could supply the required construction material.

But there is one big problem -- about ten million million tons -- in connection with the Mars elevator, and that's the inner moon, Phobos. Moving almost exactly in the equatorial plane, it would slice through the elevator at very frequent intervals. Phobosis much too big to tow away, and blowing it up would only make matters worse. I refer you to *The Fountains of Paradise* for one solution....

DYNAMIC SYSTEMS

A daring extension of the space elevator principle has been put forward by Hans Moravec of Stanford

University [17]. He imagines a'skyhook' which is at a very low altitude, and is therefore not stationary with respect to the earth, but orbiting around it.

Consider a very elongated satellite in a two hour orbit, rotating like a propeller blade (remember them?) as it rolls around the equator. The blades are just long enough to touch the earth, and if everything is properly synchronized, the tips would always touch the *same*spots on the equator at regular intervals.

From the point of view of the earth it would be, as Dr. Robert Forward has put it, 'a Jacob's Ladder coming down out of the sky, pausing for a moment, then lifting off again at 1.4 g'. One could grab hold of the end, and get a free lift into space -- and of course come back the same way.

It's a delightful concept, but the presence of the atmosphere, not to mention the fact that the equator isn't a perfect circle, and a few other practical details, make it rather unlikely. However, something similar may be possible in space, because very large rotation systems might serve as 'velocity banks' an idea discussed by Pearson and Sheffield [9,15].

If you could hook on to the edge of a spinning disc -- or an asteroid with a long extension from its equator -- you could let go again at the appropriate point and so obtain a major velocity change without using any propellant. However, we would need such an enormous number of these 'cosmic carousels' scattered round the solar system that the idea is not really practical, except perhaps for very special applications.

I'd like to conclude this section on 'dynamic systems' by mentioning, even more briefly, an idea that has just emerged from Japan [19]_the 'Space Escalator'.

Imagine two satellites in circular orbits above the equator, one a few hundred kilometres above the other. Each carries a launching mechanism and a catching mechanism, which could be something as simple as a hook and elastic cord. By means of this mechanism, payloads could be transferred in either direction without the use of propellant. With a whole series of satellites -- about a hundred -- you could hop, or leap-frog, all the way up to the stationary orbit. But it would be a computational and operational nightmare, keeping track of all the constantly changing orbits, and launching and catching payloads at the right time. I think I'll stick to the elevator, rather than take the escalator.

POWER AND PROPULSION

The physics laboratories of British schools once boasted -- and probably still do -- an instructive device known as Atwood's Machine. I don't know what it's called elsewhere, and in any case Galileo was first with something very similar. It's an almost frictionless pulley over which runs a light cord, with equal weights suspended on either side. In this state nothing happens, of course, but even a small additional weight on one side sets the system in motion, at a very low acceleration.

This device may be regarded as the mechanical analogue of the Space Elevator. I don't suggest for a moment that we would actually use moving cables to lower and raise our payloads, but it demonstrates the basic principles involved. Such a system is inherently *conservative* -- if it's properly balanced, it requires *no* energy to run it, except the very small amount lost by friction. In principle, arbitrarly large masses can be raised or lowered through any distance. Unlike the rocket, which wastes precisely 100% of its available energy on a round trip, Atwood's machine wastes only a few percent. And it's a lot quieter.

In practice, the space elevator would almost certainly be electrically powered, and the energy generated by the returning payloads during the braking and descent would be pumped back into the system -- as happens with electric railroads in mountainous country. But there is also another reason why electric propulsion would be mandatory.

Though inanimate payloads might be in no hurry to reach the geostationary orbit, 36000 km up, human passengers are easily bored and have to be fed, entertained or at least tranquillised by alcohol and inflight movies. By the time the space elevator is likely to be operating, no journey on Earth will last more than a couple of hours. I don't think that the average space tourist will tolerate a great deal of time in what will be little more than a glorified elevator cage, though one with a magnificient view.

So we will require operating speeds of several thousand kilometres an hour, which can be provided only by some kind of electric propulsion system with*no mechanical contact* -- a linear motor, for example.

I am not competent to discuss the problems involved in switching huge amounts of electric power over distances a hundred times greater than those encountered in terrestrial systems. Presumably superconductors will be available by the time the elevator is built, but the weight penalty of the associated cooling systems may make them quite impracticable. It would be marvellous, of course, if our superstrength material was *also* a superconductor -- and at room temperature (or higher)! But to expect not merely one but *three* miracles simultaneously is a little greedy.

Perhaps we can avoid enormously long transmission lines by using microwave or laser beams to get the power where it is wanted. And if it ever proves possible to build *small* nuclear generators, then perhaps we can hang the power stations at strategic points along the elevator.

However, this suggests an even more attractive possibility. There is no *theoretical* reason why small fusion -- or even fission -- generators cannot be built. If they prove to be practicable, then we could forget electrical transmission systems altogether and put the power plants in the vehicles. This would not be a retrograde step, because the weight of the 'fuel' would be essentially zero.

The space elevator could even make possible a far more efficient *chemically* fuelled transport system. In this case, the Earth-orbit structure would merely provide physical support -- the railbed, as it were, for theequivalent of a self-contained diesel locomotive, not a centrally-powered electric one. Unlike a rocket, the space-train would not have to use much of its fuel merely to *maintain* altitude; it could do that simply by putting on the brakes. On the other hand, it would be at a disadvantage over the rocket as it would have to lift some of its propellants all the way to the stationary orbit. I have not calculated at what particular specific impulse the chemical *elevator* will be more efficient than the chemical *rocket*.

SUBSIDIARY PROBLEMS

As is well known, satellites in the geostationary orbit will not normally stay above the same point on the equator, but drift in longitude owing to the fact that the Earth's gravitational field is not symmetrical. However, there are two points of maximum stability -- one in the Pacific over the Galapagos, and the other above the Maldive Islands, seven hundred kilometres to the southwest of Sri Lanka. The latter point is the more stable; by an odd coincidence, it is directly above the small island of Gan, which in the 1960s was one of the staging posts for the Blue Streak rocket when it was being ferried from the United Kingdom to the Woomera launching site. If orbital stability is important, Gan -- abandoned by the Royal Air Force several years ago, to the great distress of its inhabitants, though not of the central Maldivian government -- may one day be the most important piece of real estate on Earth.

Other orbital perturbations -- including ones in the north-south direction -- are caused by the Sun and Moon. Probably all of these are only important to free satellites, and will be insignificant in a structure which is tethered to the ground. In any case, the upper section of the elevator could -- and probably would -- sway through an arc many thousands of kilometres across without causing operational problems.

The effect of hurricanes on the lower portion of the structure has worried some writers; although high winds are rare on the equator itself, they *can* occur, and if they did nothing else they would generate severe torsional vibrations which our revered colleague Dr. von Karman studied in connection with the ill-fated Tacoma Narrows Bridge. So it might be worthwhile siting the structure on a very high mountain to reduce aerodynamic loads; unfortunately, there aren't any high mountains near the stable points.

A RING AROUND THE WORLD

There are now scores of satellites in the geostationary orbit, and the problem of collision and interference -- which not long ago would have seemed an absurd fantasy -- is already of practical importance. What is more, some equatorial countries are attempting to establish jurisdiction over this large but still restricted narrow ring around our planet. This has provoked the appalling pun, which perhaps fortunately cannot be translated from English, that there should be another U.N. Committee -- on the Useful Pieces of Outer Space

In 1977, while working on the final chapters of *The Foundains of Paradise,* I had one of those sudden glimpsess of the perfectly obvious out of which I have cunningly fashioned my reputation as a prophet. One way of preventing geostationary satellites colliding or drifting around the equator would be to link them together with cables. As the forces involved would be**extremely small,** for the most purposes nothing much stronger than a nylon fishing line would be adequate, and the total mass needed to tie together all the satellites in the stationary orbit would be negligible.

But why stop there? The next step would be to build a continuous, habitable structure -- a 'Ring City' -- right around the Earth. All the legions of geostationary satellites could be attached to it, and reached for servicing by an internal circular railroad. And it could serve as a launch platform for almost all missions, manned or unmanned, into deep space.

It would be reached, of course, by space elevators, which would take the form of several spokes linking the ring city with the equator. The Earth would, in fact, now be the hub of a gigantic wheel, 85000 km in diameter. Passengers could move up and down the spokes, or around the rim, just as freely as they now move around the surface of the Earth. The distinction between Earth and space would be abolished, though the advantages of either could still be retained.

A Russian engineer, G. Polyakov had the same idea almost simultaneously, and published a paper with the title 'A space necklace about the Earth'[20]. However, as I might have guessed, we were both anticipated by Professor Buckminster Fuller. To quote from the notes he wrote for the sleeve of my Fountains of Paradise recording (Caedmon TC 1606):

'In 1951, I designed a free floating tensegrity ring-bridge to be installed way out from and around the Earth's equator. Within this halo bridge, the Earth could continue its spinning while the circular bridge would revolve at its own rate. I foresaw Earthian traffic vertically ascending to the bridge, revolving and descending at preferred Earth loci.'

All that Bucky's vision needs to make it reality is the space elevator

And when will we have that? I wouldn't like to hazard a guess, so I'll adapt the reply that Arthur Kantrowitz gave, when someone asked a similar question about his laser propulsion system

The Space Elevator will be built about 50 years after everyone stops laughing.

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Finally, I am especially grateful to Mr Vladimir Lvovfor giving me biographical material on Yuri Artsutanov (Born 1929, Leningrad) and for putting me in touch with him. Indeed, while this paper was in its final draft I was delighted to receive a letter from Mr Artsutanov (dated April 1979) of such interest and importance that it demands quoting at length:

'It may be interesting for you to know how the idea of the space elevator (s.e.) originated. At the beginning of 1957 a friend of mine, who like myself graduated at the Leningrad Technological Institute.. . told me about a material which could hold its weight at the length of 400km. I thought that at such a height the gravitating force is less and consequently the length could be enlarged. Then it became interesting for me to calculate the strength of the material to prolong the vertical rod made of it to infinity.... Immediately the thought came that this rod should have a changeable section and it was easy to derive the equation . .. which showed that the rod could be done out of any material and its mass did not become absurdly large....

'At first I told some of my friends about this idea. Some months later the cosmic theme became very popular. In Summer 1960 I was in Moscow on business and visited the editor of Komsomolskayu Pravda with a proposal to publish my article without any equations. .. to my mind, they could be derived by any student who understood the idea. A week later the article was published under the title "Into space with the help of an electric locomotive. . .";

'In 1969 the magazine Knowledge is Force (Znanije-Sila) No. 7, p. 25, published my article developing the idea of the s.e. It was proposed to sink the rods not from a synchronous satellite but from an ordinary one, for example 1000km, height. In this case the contact with Earth and the passing of denser layers of the atmosphere would take place at a comparative low speed. The rods would be like spokes of a wheel rolling along the equator....Having attached itself to the end of such a rod during a half-turn of this wheel the cosmic ship will gain the speed of 14 km/s. Similarly the ship returning from the cosmic space will lose the speed and land during another half turn....'

It will be seen that this proposal is virtually the same as that put forward by Moravec 8 years later [17].

Until now, Yuri Artsutanov's work has only been published in simplified form for the benefit of the lay public. Let us hope that it will soon appear in its original version, so that his peers can fully appreciate the full genius of this remarkable Leningrad engineer.

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