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

by ARTHUR C. CLARKE

Chancellor, University of Moratuwa, Sri Lanka

-- *Fellow of King's College, London.*

Address to the XXXth International Astronautical Congress, Munich, 20 September 1979.

Abstract -- The space elevator *(alias Sky Hook, Heavenly Ladder, Orbital Tower, or Cosmic Funicular)*is a structure linking a point on the equator to a satellite in the geostationary orbit directly above it. By providing a 'vertical railroad' it would permit orders-of-magnitude reduction in the cost of space operations. The net energy requirements would be almost zero, as in principle all the energy of returning payloads could be recaptured; indeed, by continuing the structure beyond the geostationary point (necessary in any event for reasons of stability) payloads could be given escape velocity merely by utilising the 'sling' effect of the Earth's rotation.

The concept was first developed in detail by a Leningrad engineer, Yuri Artsutanov, in 1960 and later by several American engineers quite unaware of Artsutanov's work. All studies indicate that the idea, outrageous though it appears at first sight, is theoretically feasible and that its practical realisation could follow from the mass-production of high-strength materials now known as laboratory curiosities.

This paper is a semi-technical survey of the rapidly expanding literature of the subject, with some speculations about ultimate developments. Whether or not the Space elevator can be actually built, it is of great interest as the *only* known device which could replace the rocket as a means of escaping from the earth. If it is ever developed, it could make mass space travel no more expensive than any other mode of transportation.

INTRODUCTION

WHAT I want to talk about today is a space transportation system so outrageous that many of you may consider it not even science-fiction,but pure fantasy. Perhaps it is; only the future will tell. Yet even if it is regarded as no more than a 'thought-experiment', it is one of the most fascinating and stimulating ideas in the history of astronautics

This paper is essentially a survey; in the unlikely event that it contains anything original, it's probably wrong. Your complaints should be addressed to Director-General Roy Gibson, who is responsible for getting me here.

What's in a name?

First of all, we have a severe problem in nomenclature. It is very difficult to talk about something, until people have agreed on its name. In this case, we have an embarrassingly wide choice.

The Russian inventor used the charming 'heavenly funicular'. American writers have contributed 'orbital tower', 'anchored satellite', 'beanstalk', 'Jacob's Ladder -- and, of course, 'Skyhook'. I prefer'space elevator'; it is euphonious (at least in English) and exactly describes the subject.

Historical

As usual, it all began with Tsiolkovski -- specifically, with his 1895 paper 'Day-Dreams of Heaven and Earth' [1]. During his discussion of possible ways of escaping from the earth, he considered the building of a high tower, and described what would happen as One ascended it. I quote:

'On the tower, as one climbed higher and higher up it, gravity would decrease gradually; and if it were constructed on the Earth's equator and, therefore, rapidly rotated together with the earth, the gravitation would disappear not only because of the distancefrom the centre of the planet, but also from the centrifugal force that is increasing proportionately to that distance. The gravitational force drops. . . but the centrifugal force operating in the reverse direction increases. On the earth the gravity is finally eliminated at the top of the tower, at an elevation of 5.5 radii of the earth (36000 km).

'As one went up such a tower, gravity would decrease steadily, without changing direction; at a distance of 36000 km, it would be completely annihilated, and then it would be again detected. . . but its direction would be reversed, so that a person would have his head turned towards the earth....'

Tsiolkovski then calculates the height of similar towers on the Sun and planets, but his comments -- at least as I read the translation ('it would be excessive to discuss how possible these towers would be on the planets' he suggests that he does not regard the concept as a serious practical proposition. And of course he is quite right: it would be impossible, if I dare use such a risky word, to constructfree-standing towers tens ofthousands of kilometres high. If Tsiolkovski failed to mention the alternative solution, it may be because he was concerned only with the first steps away from earth. And the space-elevator is completely useless in the pioneering days of astronautics, unless you are lucky (?) enough to live on a very small, rapidly spinning planet.

Nevertheless, it is interesting to find how high atower we could build, if we really tried. In early 1962the Convair Division of General Dynamics carried out a feasibilitystudy, to see if very high towers would be of value for astronomy, high altitude research,communications and rocket launching platforms [2]. It turns out that steel towers could be built up to 6km high, aluminium ones up to almost 10. Nature can do just as well; it wouldbe cheaper to use Mount Everest.

However, we now have much better materials than steel and aluminium in the form of composites, which give both high strength *and* low density. Calculations show that a tower built of graphite composite struts could reach the very respectable height of 40 km, tapering from a 6 km-wide base. I dare not ask what it would cost; but it's startling to realise that, even with today's technology, we could build a structure *100 times* as high as the world's tallest building.

But the geostationary orbit is a thousand times higher still, so we can forget about building up towards it. If we hope to establish aphysical link between Earth and space, we have to proceed in the opposite direction -- from orbit, down-wards.

That it might be useful to hang a long cable from a satellite must have occurred to a great many people. I myself toyed with the idea in 1963 while preparing an essay on comstats for UNESCO, published next year in*Astronautics [3*]. At that time, there was stillconsiderable uncertainty about the effects of the time delay in satellite telephone circuits; some thought that it might have proved intolerable in ordinary conversation.

Although we should be duly grateful to Nature for giving us the geostationary orbit, one can't help wishing, for INTELSAT'S sake, that it was a good deal closer. So I wondered if it would be possible to suspend a satellite repeater 10000 or more kilometres below the 36000 km altitude that the law of gravity, and the Earth'srotational speed, has dictated.

Some desultory calculations soon convinced me that it couldn't be done with existing materials, but as I wanted to leave the option open I wrote cautiously: 'As a muchlonger-term possibility, it might be mentioned that there are a number of theoretical ways of achieving a low-altitude, twenty-four hour satellite; but they depend upon technical developments unlikely to occur in this century. I leave their contemplation as "an exercise for the student"!' In 1969, 6 years later, Collar and Flower came to exactly the same conclusion in a *J.B.I.S.* paper 'A (relatively) low altitude 24-h satellite' [4]. To quote their summary:

'The scheme for launching a twin-satellite system into a 24-h orbit with the inner satellite relatively close to the earth's surface is theoretically possible, although with the materials currently available no operational advantage would result. New materials now being developed, however, if used to the limit of their strength, could result in a system that considerably improved communication efficiency. Even with materials that are strong enough and light enough many problems exist. Static and dynamic stability investigations would need to be made, and temperature effects allowed for. In the design of the system, means of deployment and of minimising meteorite damage would in particular need careful consideration.

'The final conclusion is that while theoreticaly possible, the twin satellite system is impractical at the present time, but will show ever increasing promise as new, strong, light materials are developed

Incidentally, Collar and Flower did mention that it would be possible for the cable to reach *all the way down to the Earth's surface,* though they did not elaborate on this point, and were apparently unaware of earlier work in this field. For it now appears that at least half a dozen people invented the space elevator quite independently of each other, and doubtles more pioneers will emerge from time to time.

In the West, the group that got there first consisted of John Isaacs, Allyn Vine, Hugh Bradner and George Bachus, from the Scripps Institute of Oceanography and the Woods Hole Oceanographic Institute. It is, perhaps, hardly surprising that oceanographers should get involved in such a scheme, since they are about the only people who concern themselves with very long hanging cables. Very long, that is, by ordinary standards; but in their 1966 letter to *Science [5]* Isaacs*et al*. discussed a cable over *three thousand* times longer than one to the bottom of the Marianas Trench, a mere 11 km down.

Their brief but very comprehensive paper made the following points:

The cable would have to be tapered, and would have to be spun out in both directions simultaneously -- that is, towards the Earth and away from it, so that the structure was always balanced around the geostationary point. One would start with the smallest possible cable -- perhaps with a minimum diameter of only a few thousandths of a centimetre -- and the lower end would have to be guided down to earth by some kind of reaction device. Once the initial cable had been established between stationary orbit and the point on the equator immediately below it, it could be used to establish a stronger cable, until one of the required carrying capacity was attained. In principle, it would then be possible to hoist payloads from earth into space by purely mechanical means.

Now, you will recall that, as one ascends Tsiolkovski's hypothetical space tower, gravity decreases to zero at stationary orbit -- *and its direction then reverses itself*. In other words, though one would have to do work to get the payload up to the geostationary position, once it had passed that point it would continue to travel on outwards, at an increasingacceleration -- falling upwards, in fact. Not only would it require no energy to move it away from earth -- it could*generate* energy, which could be used to lift other payloads! Of course, this energy comes from the rotation of the earth, which would be slowed down in the process. I have not attempted to calculate how much mass one could shoot off into space before the astronomers complained that their atomic clocks were running fast. It would certainly be a long time before anyone else could notice the difference....

Isaacs *et al*. go on to say:

'In addition to their use for launching materials into space, such installations could support laboratories for observation of conditions in space at high altitudes; they could resupply energy or materials to satellites or spacecraft, collect energy or materials from space and the high atmosphere, support very tallstructures on the earth's surface, and others. There isno immediate limit to the total mass that could be retained near the l-day orbit by such a cable.'

Isaacs *et al.,* discussed only briefly the obviouslyvital question of possible materials, listing amongst others quartz, graphite and beryllium. The *total* mass, with the best material, of a cable strong enough towithstand 200kmh[-1] wind forces, turns out to be surprisingly low -- only half a ton! Needless to say, its diameter at the earth and would be extremely small -- one five-hundredth of a centimetre. And before anyone starts to spin this particular thread, I should point out that the material proposed is quite expensive. I don't know what the market quotation would be for half a ton of -- *diamond*.

The first reaction to the Isaacs paper came some three months later [6] when an unlucky American scientist fell into a neat dynamical trap. He was not the only one to do so, apparently; but James Shea was unfortunate enough to have his letter published. The objection he raised was ingenious and so apparently convincing that he stated flately: 'The system is inefficient as well as mechanically unsound and*theoretically* impossible.' (My italics.)

Shea's paradox can best be appreciated as follows: Consider the payload to be sent up the cable, when it is resting on the equator at the beginning of its journey. Obviously, because of the Earth's spin, it's actually moving eastwards at about 1700 km h.

Now it is sent up the cable --*how it is, is for the moment, unimportant* -- until it reaches the geostationary orbit, 36000km above the Earth. It is still exactly above the point from which it started, but almost six times further from the centre of the Earth. So to stay here, it must obviously move six times faster -- about 11000kmh~l. How does it acquire all this extra tangential velocity?

There's no problem when you consider the analogous case of a fly crawling from the hub out along the spoke of a spinning wheel. The wheel is a rigid structure, and automatically transmits its rotational velocity to the fly. But how can a flexible cable extending out into space perform the same feat?

The explanation may be found by looking at one of mankind's simplest, oldest and most cost-effective weapons -- the sling. I wonder if Goliath's technical advisers told him not to worry about that kid with the ridiculous loop of cloth -- it couldn't possibly transfer any kinetic energy to a pebble. If so, they forgot that the system contained a rigid component -- David's strong right arm. So also with the space elevator. Its lower end is attached to the 6000 km radio of the Earth -- quite a lever.

Having easily refuted this criticism, Isaacs & Co. were now in for a shock. More than a year after their letter had appeared, *Science* printed a lengthy note [7] from Vladimir Lvov, Moscow correspondent of the Novosti Press Agency, pointing out that they had been anticipated by a half a decade. A Leningrad engineer, Yuri N. Artsutanov, had already published an article in*Pravda* which not only laid down *all* the basic concepts of the space elevator, but developed them in far greater detail.

This 1960 paper, which may turn out to be one of the most seminal in the history of astronautics, has the unassuming title 'Into the Cosmos by electric vehicle'. Unfortunately, it has never been translated into English, nor have the extensive calculations upon which it is obviously based yet been published. The summary that follows is therefore based on Lvov's letter.

Artsutanov's initial minimum cable, constructed from materials which already exist but which have so far only been produced in microscopic quantities, would be able to lift two tons, would have a diameter of about one millimetre at the earth's surface, and would have a total mass of about 900 tons. It would extend to a height of 50000 km -- that is, 14000km beyond geostationary altitude, the extra length providing the additional mass needed to keep the whole system under tension. (The weight, as it were, on the end of the sling.)

But this is just a beginning. Artsutanov proposed to use the initial cable to multiply itself, in a sort of boot-strap operation, until it was strengthened a thousand fold. Then, he calculated, it would be able to handle 500 tons an hour or 12000 tons a day. When you consider that this is roughly equivalent to one Shuttle flight every minute, you will appreciate that Comrade Artsutanov is not thinking on quite the same scale as NASA. Yet if one extrapolates from Lindbergh to the state of transatlantic air traffic 50 yr later, dare we say that he is over-optimistic? It is doubtless a pure coincidence, but the system Artsutanov envisages could just about cope with the current daily increase in the world population, allowing the usual 22 kg of baggage per emigrant....

Lvov uses two names to describe Artsutanov's invention: a 'cosmic lift', and a 'heavenly funicular'. But a funicular, strictly speaking, is a device operated by a rope or cable -- and we may be sure that the space elevator will not hoist its payloads with the aid of moving cables tens of thousands of kilometres long.

One would have thought that this correspondence, in one of the world's leading scientific journals, would have triggered a large scale discussion. Not a bit of it; to the best of my knowledge, there was no reaction at all. This may be because the Apollo project was then moving towards its climax -- the first moon landing was less than two years away -- and everyone was hypnotised by big rockets, as well they might be.

But the idea must have been quietly circulating in the U.S.S.R. because it is illustrated in the handsome volume of paintings by Leonov and Sokolov "The Stars are Awaiting Us" (1967). On p. 25 there is a painting entitled 'Space Elevator', showing an assembly of spheres -- hovering, I am pleased to see, over Sri Lanka -- from which a cable stretches down to the earth. Part of the descriptive text reads as follows:

'If a cable is lowered from the (24 h) satellite to the earth you will have a ready cable-road. An "Earth-Sputnik-Earth" elevator for freight and passengers can then be built, and it will operate without any rocket propulsion.'

Rather surprisingly, there is no reference to the inventor. Sokolov's original painting, incidentally, hasbeen acquired by my insatiably acquisitive friend Fred Durant for the National Air and Space Museum, which by now must surely have the world's finest collection of space art (and space hardware).

The next major development was not for another *eight*years. Then Jerome Pearson of the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, invented the idea all over again and published the most comprehensive study yet in *Acta Astronautica [8]*. His computer search of the literature had failed to turn up any prior references, and in view of the indexing problem I'm not surprised. How would you look up such a subject? Pearson called it an 'orbital tower', and presumably never thought of telling his computer to hunt for 'sky-hook', which might have located the*Science* correspondence.

I speak with some feeling on this, because for 2 years I was solely responsible for indexing *Physics Abstracts,* and you'll find some very strange entries round 1950. But the problem is insoluble, unless you can do retrospective re-indexing. When a new phenomenon is discovered, you may not even know how to classify it, let alone what to call it (after all, we're still stuck with X-rays, after almost a century. . .).

Pearson's 1975 paper was the most thorough study of the project yet published, and emphasised one of the space elevator's most important characteristics. Like a terrestrial elevator, it *could be used in both directions*. Returning payloads could be brought back to Earth without the use of heat-shields and atmospheric braking. Not only would this reduce environmental damage; it would mean that virtually all the energy of re-entry could be recovered, and not wasted as is the case today.

This characteristic makes the space elevator unique -- at least, until someone invents anti-gravity. *It is a conservative system*. If, as would probably be the case, electrical energy is used to lift payloads up the elevator, and the mass flow is the same in both directions, incoming traffic could provide all the energy needed to power outgoing traffic. In practice, of course, there could be the inevitable conversion and transmission losses, but they could be quite small.

In this and subsequent papers [9] Pearson was the first to go into the dynamics of the system, discussing the vibration modes of the structure due to launch loads, gravity, tides etc. He decided that none of these, **though important,** would cause any insuperable problems. Indeed, I have suggested elsewhere that they could even be used to advantage [10].

Pearson has also located at least three other independent originators of the concept [11], though none prior to Artsutanov's 1960 paper. From now on, at least, further re-invention is unnecessary; however, as we shall see later, novel and often surprising extensions of the basic system are still appearing.

continue

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THE PROBLEM OF MATERIALS

The very minimum requirement for a space elevator is, obviously, a cable strong enough to support its own weight when hanging from geostationary orbit down to earth, 36000 km below. That is a very formidable challenge; luckily, things are not quite as bad as they look because only the lowest portion of the cable has to withstand one full gee.

As we go upwards, gravity falls off according to Newton's inverse square law. But the *effective weight* ofthe cable diminishes even more rapidly, owing to the centrifugal force on the rotating system. At geostationary altitude the two balance and the net weight is zero; beyond that, weight appears to increase again -- but *away* from the Earth.

So our cable has no need to be strong enough to hang 36000 km under *sea-level* gravity; allowing for the effects just mentioned, the figure turns out to be only one-seventh of this. In other words, if we could manufacture a cable with sufficient strength to support 5000 km (actually, 4960) of its own length at one gee, it would be strong enough to span the gap from geostationary orbit to Equator. Mathematically -- though not physically -- Jacob's ladder need be only 5OOOkm long to reach Heaven.... This figure of 5000km I would like to call 'escape length', for reasons which will soon be obvious.

How close are we to achieving this with known materials? Not very. The best steel wire could manage only a miserable 5O km or so of vertical suspension before it snapped under its own weight. The trouble with metals is that, though they are strong, they are also heavy; we want something that is both strong and *light*. This suggests that we should look at the modern synthetic and composite materials. Kevlar (Tm) 29, for example [12] could sustain a vertical length of 200 km before snapping -- impressive, but still totally inadequate compared with the 5000 needed.

This 'breaking length', also known as 'rupture length' or 'characteristic length', is the quantity which enables one to judge whether any particular material is adequate for the job. However, it may come as a surprise to learn that a cable can hang vertically for a distance many times greater than its breaking length!

This can be appreciated by a simple 'thought experiment'. Consider a cable which is just strong enough to hang vertically for a hundred kilometres. One more centimetre, and it will snap....

Now cut it in two. Obviously, the upper 50 km can support a length of 50 km -- the identical lower half. So if we put the two sections side by side, they can support a *total* length of 100 km. Therefore, we can now span a vertical distance of 150 km, using material with only 100 km breaking length.

Clearly, we can repeat the process indefinitely, bundling more and more cables together as we go upwards. I'm sure that by now you've recognised an old friend -- the 'step' principle, but in reverse. Step *rockets*get smaller as we go higher; step cables get bigger.

I apologise if, for many of you, I'm labouring theobvious, but the point is of fundamental importance and the rocket analogy so intriguing that I'd like to take it a little further.

We fossils from the pre-space age -- the Early Paleoastronautic Era -- must all remember the depressing calculations we used to make, comparing rocket exhaust velocities with the 11.2 km 5' of Earth escape velocity. The best propellants we knew then --

and they are *still* the best today! -- could provide exhaust velocities only a quarter of escape velocity. From this,some foolish critics argued that leaving the Earth by chemicalrocket was impossible even in *theory[13*].

The answer, of course, was the step or multi-stagerocket -- buteven this didn't convince some sceptics. Willy Ley [14] recordsa debate between Oberth and a leading German engineer, who simplywouldn't believe that rockets could be built with a mass-ratio oftwenty. For Saturn V, incidentally, the figure is about fivehundred

We escaped from earth using propellants whose exhaust velocitywas only a fraction of escape velocity, by paying the heavy pricedemanded by multi stage rockets. An enormous initial mass wasrequired for a small final payload.

In the same way, we can achieve the 5000 km 'escape length', evenwith materials whose breaking length is a fraction of this, bysteadily thickening the cable as we go upwards. Ideally, thisshould be done not in discrete steps, but by a continuous taper.The cable should flare outwards with increasing altitude, itscross-section at any level being just adequate to support theweight hanging below.

With a stepped, or tapered, cable it would be theoreticallypossible to construct the space elevator from any material,however weak. You could build it of chewing gum, though the totalmass required would probably be larger than that of the entireuniverse. For the scheme to be practical we need materials with abreaking length a very substantial fraction of escape length.Even Kevlar 29's 200 km is a mere 25th of the 5000 km goal; touse that would be like fuelling the Apollo mission with dampgunpowder, and would require the same sort of astronomicalratio.

So, just as we were once always seeking exotic propellents, wemust now search for super-strength materials. And, oddly enough,we will find them in the same place on the periodic table.

Carbon crystals have now been produced in the laboratory withbreaking lengths of up to 3000km -- that is, more than *half*of escape length. How happy the rocket engineers would be, ifthey had a propellant whose exhaust products emerged with 60% ofescape velocity!

Whether this material can ever be produced in the megatonquantities needed is a question that only future technologies cananswer; Pearson [8] has made the interesting suggestion that thezero gravity and vacuum conditions of an orbiting factory mayassist their manufacture, while Sheffield [15] and I [10] havepointed out that essentially unlimited quantities of carbon areavailable on many of the asteroids. Thus when space mining is infull swing, it will not be necessary to use super-shuttles tolift vast quantities of building material up to geostationaryorbit -- a mission which, surprisingly, is somewhat moredifficult than escaping from Earth.

It is theoretically possible that materials stronger -- indeed,vastly stronger -- than graphite crystals can exist. Sheffield[153 has made the point that only the outer electrons of theatoms contribute, through their chemical bonds, to the strengthof a solid. The nucleus provides almost all the mass, but nothingelse; and in this case, mass is just what we don't need.

So if we want high-strength materials, we should look at elementswith low atomic weights -- which is why carbon (A.W.12) is goodand iron (A.W.56) isn't. It follows, therefore, that the bestmaterial for building space elevators is -- solid hydrogen! Infact, Sheffield calculates that the breaking length of a solidhydrogen crystal is 9118 km -- almost twice 'escape length'.

By a curious coincidence, I have just received a press releasefrom the National Science Foundation headed 'New form of hydrogencreated as Scientists edge closer to creating metallichydrogen'[16]. It reports that, at a pressure of half a millionatmospheres, hydrogen has been converted into a *densecrystalline solid at room temperature*. The scientistsconcerned go on to speculate that, with further research -- and Iquote -- "hydrogen solids can be maintained for long periodswithout containment".

This is heady stuff, but I wonder what they mean by 'longperiods'. The report adds casually that 'solid hydrogen is 25 to35 times more explosive than TNT'. So even if we *could*make structures from solid hydrogen, they might add a newdimension to the phrase 'catastrophic failure'.

However, if you think that crystallitic hydrogen is a trickybuilding material, consider the next item on Dr. Sheffield'sshopping list. The ultimate in theoretical strength could beobtained by getting rid of the useless dead mass of the nucleus,and keeping only the bonding electrons. Such a material hasindeed been created in the laboratory; it's 'positronium' -- theatom, for want of a better word, consisting of electron-positronpairs. Sheffield calculates that the breaking length of apositronium cable would be a fantastic 16,700,000km! Even in theenormous gravity field of Jupiter, a space elevator need have noappreciable taper.

Positronium occurs in two varieties, both unfortunately ratherunstable. Para-positronium decaysinto radiation in one-tenth of ananosecond -- but orthopositronium lasts a thousand times longer,a whole tenth of a microsecond. So when you go shopping forpositronium, make sure that you buy the brand marked 'Ortho'.

Sheffield wonders wistfully if we could stabilise positronium,and some even more exotic speculations are made by Moravec [17].He suggests the possible existence of 'monopole' matter, andhybrid 'electric/magnetic' matter, which would give not onlyenormous strength but superconductivity and other usefulproperties.

Coming back to earth -- or at least to this century -- it seemsfair to conclude that a small cable could certainly beestablished from geostationary orbit down to sea level, usingmaterials that may be available in the near future. But that, ofcourse would be only the first part of the problem -- a meredemonstration of principle. To get from a simple cable to aworking elevator system might be even more difficult. I would nowlike to glance at some of the obstacles, and suggest a fewsolutions; perhaps the following remarks may stimulate othersbetter qualified to tackle them.

continue

Part 3 of 3

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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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