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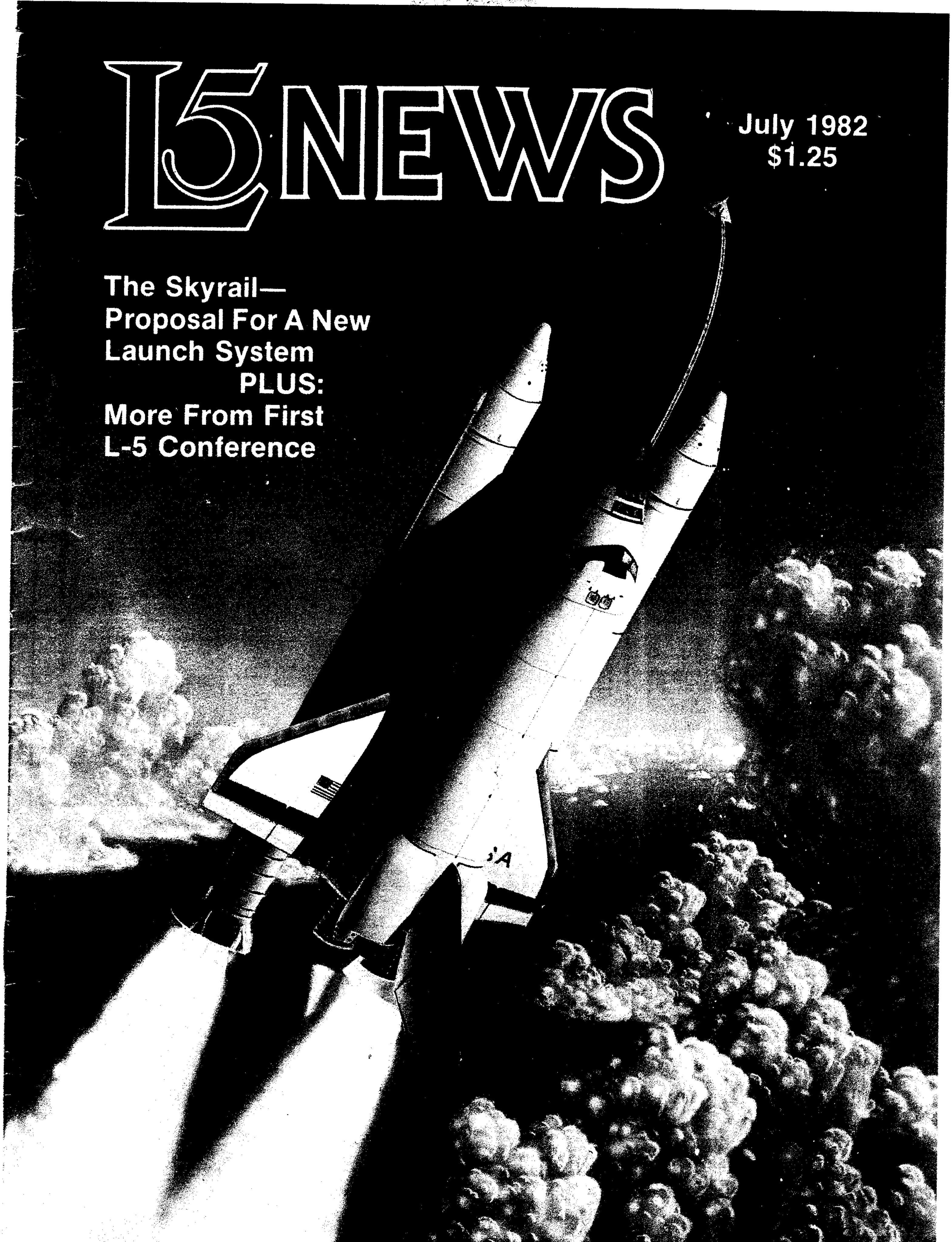


**The Skyrail—
Proposal For A New
Launch System
PLUS:
More From First
L-5 Conference**

Launching Pad:

THE SKYRAIL

by Kenneth A. Brakke

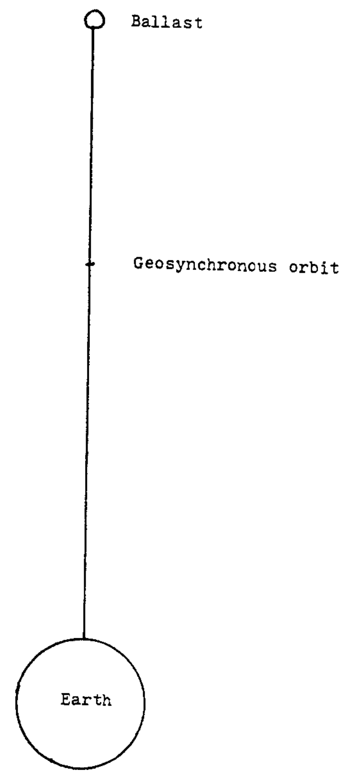


Figure 1. Geosynchronous skyhook. The weight of the cable hanging below geosynchronous orbit is balanced by the centrifugal force on the mass beyond.

Introduction

Logically, civilization should spread from the Earth into outer space. (ref. [1]) But the high cost of getting into orbit has been a formidable barrier to such plans. The Space Shuttle will cost perhaps $1000 per kilogram payload to orbit. If outer space is truly to be opened up, one must figure on the order of 100,000,000 passenger trips to space each year. The Space Shuttle will have difficulty doing this, to put it mildly. Ideally, fares to orbit should be in the same range as current airline fares, up to several dollars per kilogram.

This is not a theoretical impossibility. The actual energy of an orbiting kilogram is the equivalent of about 10 kilowatt-hours of electricity, worth $1.00 or less at today's prices. If a surface-to-orbit transportation system could achieve just 20% of the theoretical efficiency, then the universe could be ours.

High efficiency requires that the payload be most of the mass of the vehicle and that acceleration be done by pushing against a fixed mass. This means an external power supply and a physical, material guideway from the Earth's surface into orbit. On airless bodies such as the Moon, an electromagnetic accelerator such as the mass driver[1] is a solution. Large mass drivers on Earth whose telephone pole shaped payloads punch through the atmosphere by brute force have been suggested,[2] but the 1000 gee acceleration would be too much for anything as delicate as a human being.

In the 1960's, the concept of the geosynchronous skyhook was invented.[3] A cable would extend from the Earth's surface out to geosynchronous orbit and beyond, with masses so arranged that centrifugal force would balance gravity and the whole thing would stay stretched out above one spot on the surface. See figure 1. The problem with this plan is the tremendous strength needed for the cable.

The best way to compare various skyhook requirements and available materials is to translate actual skyhook cable lengths into equivalent heights of hanging cables in a constant, nonrotating one gee field, and express material strength as a characteristic height of the length of uniform cable that could support its own weight in a one gee field. Thus a geosynchronous skyhook has an equivalent height of about 4900 kilometers. The characteristic heights of some materials are listed in Table 1. Kevlar is a plastic used for tire cord and bulletproof vests that is made in hundred million pound quantities annually by DuPont.[5]

Safety factors would make the usable characteristic height less. Cable lengths greater than the characteristic height may be obtained with an exponentially tapering cross section, tapering by a factor of e = 2.7183 every characteristic height. A geosynchronous skyhook could be made if perfect graphite crystals could be made on a large scale, but so far they are small laboratory curiosities.

Hans Moravec[6] has proposed a shorter

Table 1

Material	Characteristic height,[4] km.
Steel	50
Titanium	30
Aluminum	25
Magnesium	25
Fiberglass	95
Kevlar	190
Perfect single crystals	
Alumina	800
Beryllium oxide	1000
Silicon carbide	1100
Graphite	
(observed)	3200
(theoretical)	4000
Diamond	
(theoretical)	3200

skyhook that would rotate as it orbits the Earth, the ends alternately touching down and snatching payloads.

Unfortunately, the optimum configuration still has an equivalent height of over 3000 kilometers.

The Skyrail

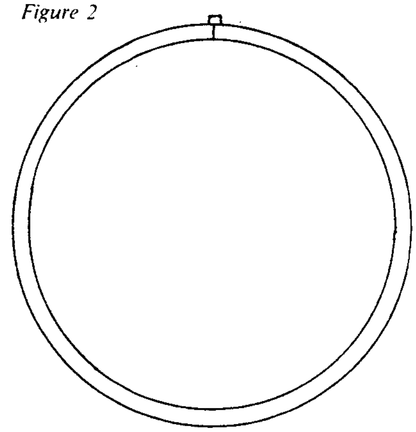
In this section, I propose a new scheme which requires a skyhook only 200 kilometers high, just enough to reach low orbit. The central feature is the Skyrail, a band of aluminum orbiting 200 kilometers above the equator and completely encircling the Earth. See figure 2. On the Skyrail would run cars supported and propelled electromagnetically. A car at rest with respect to the Earth's surface would drop a cable to the ground, and we would have a short skyhook. Other cars would take payloads from the stationary cars and accelerate them to orbital or escape velocity.

Attention must be paid to orbital mechanics in order to ensure that the whole contraption does not disintegrate. Mechanical impulses in a material travel only at the speed of sound (indeed, sound is made up of mechanical impulses). Since the speed of sound in aluminum is less than orbital speed,' a stationary car is supported only by the Skyrail immediately beneath it. The Skyrail between cars must be regarded as being in a free orbit. The weight of a car on a piece of rail as it passes will necessarily change the orbit of the piece of rail. In the brief moment that the piece passes below a car, it feels a jolt that changes its vertical momentum slightly downward. In effect, the Skyrail keeps a car up by bouncing off the bottom of it. See figure 3. The tremendous speed of the Skyrail, about 7.5 kilometers per second, means that a tremendous amount of mass passes a car each second and only a slight deflection of the Skyrail is necessary to support a fairly large car.

The key fact about orbits is that they are ellipses with one focus at the center of the Earth. A Skyrail could not support just one stationary car because when an elliptical orbit closes on itself, it connects smoothly. There can be no bounce. But two antipodal cars can be supported! Between them the Skyrail runs in the lower parts of symmetrical elliptical orbits whose perigees are midway between the cars. See figures 4 and 5.

The alert reader might object that the Earth's rotation has not been taken into account, that by the time the rail had made half an orbit from Ecuador Station, Sumatra Station would not be there. No problem. Simply aim the Skyrail for where the station will be when it gets there. This makes the Skyrail orbit between stations slightly larger than half an ellipse with the perigee of a particular piece of rail halfway between the points where that piece meets the stations.

Figure 2



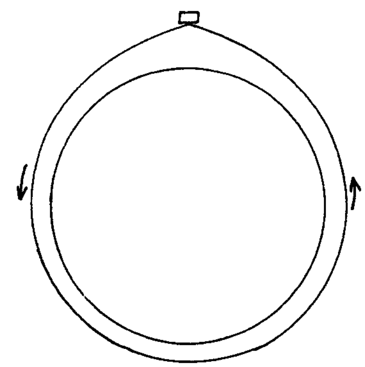


Figure 3

Figure 2. Skyrail around Earth with skyhook hanging from stationary car.

Figure 3. Skyrail bouncing off bottom of car keeps car up. But orbit shown is not an ellipse and therefore impossible.

See figure 6. To an observer rotating with the Earth, things still look like figure 5.

Let us take a more detailed look at a heavy-duty Skyrail as it might be thirty or forty years hence. The rail itself has a linear density of one ton per meter, for a total mass of 40,000,000 tons. Each station masses 100,000 tons and is one kilometer long. The rail feels an acceleration of 100 gees downward as it passes a station, and midway between the two stations the rail dips to an altitude of 155 kilometers. One station is poised above Ecuador and is thus called Ecuador Base. On the opposite side of the globe is Sumatra Station perched above Sumatra Base.

Between each Base and Station runs a continuous moving loop of high strength cable. As can be seen from Table 1, the necessary strength is well within our grasp. Payloads are attached to the cable to be lifted up to the Station or lowered down to the Base. Four guywires fan out from the Station to the ground to hold the Station in place. A high voltage transmission line runs up one guywire to provide electric power to the Station. The Station uses the power to levitate on the rail and to maneuver the rail so that the rail winds up at the right place when it reaches the antipodal Station. The momentum of the rail in all three directions can be precisely controlled, and miscellaneous perturbations can be corrected.

Small railcars run on the rail between the Stations. A car starting at a Station with a payload to be accelerated to orbital velocity need only use electromagnetic braking with respect to the rail. Decelerating from orbital velocity or accelerating to escape velocity requires more energy than can be carried in a car, so there are power storage devices in the rail that are charged as they pass the Stations and tapped by passing cars.

The construction of the first Skyrail, a hundredth of the mass of the above design, might go something like this: Using aluminum derived from the Moon or an asteroid, 400,000 rail segments are formed, each 100 meters long and weighing one ton. They are distributed along a circular orbit 200 kilometers above the equator and linked with expansion joints. The expansion joints are necessary because the rail moves faster in the lower parts of its orbit and thus stretches, by a little less than 1% for the design used here. The two Stations, each weighing 1000 tons and containing guywires and cables coiled up inside, are placed on the rail, orbiting with it. Their internal power supplies are sufficient for levitation but not for deceleration to stationary position. Therefore they drop anchor cables into the atmosphere, and atmospheric braking provides the deceleration. The anchor cables are grabbed by aircraft carriers and towed to the permanent Bases. Guywires are let down, the loop threaded, and the Skyrail is in business!

A Trip on the Skyrail

How does the Skyrail seem to a passenger? Let us suppose that you are an antimatter engineer on a trip from Chicago back

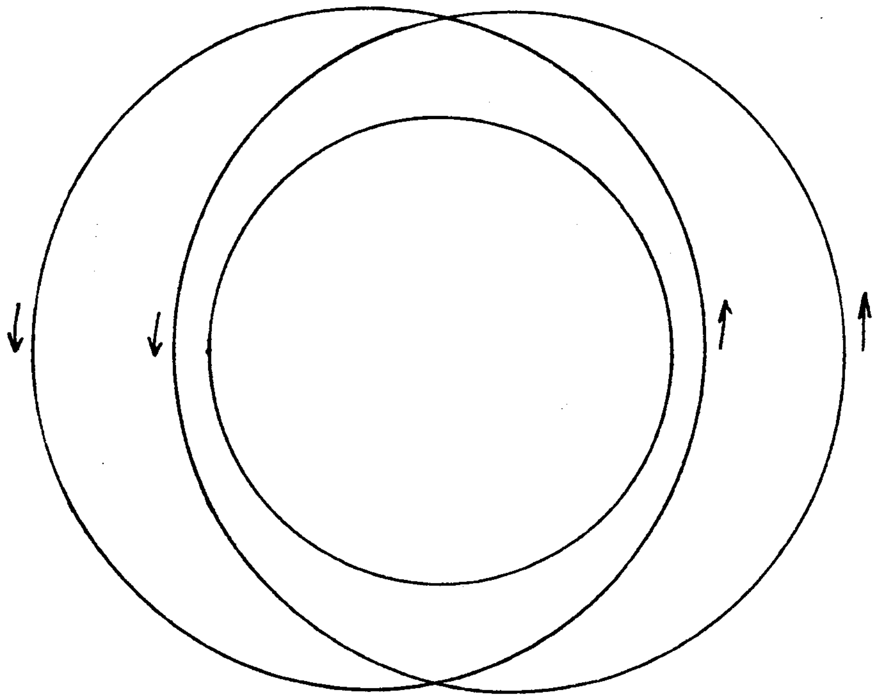


Figure 4. Two symmetrical elliptical orbits.

to Ceetee Habitat, where all antimatter experimentation is done. (Nobody wants this ultimate explosive on Earth, and it is much easier to handle in zero gee. "Ceetee" comes from "CT", or "contraterrene matter.") After checking your luggage through to Ceetee from O'Hare Airport, you fly to Ecuador Base in a standard jet. As you approach, you see the U-shaped pair of towers that house the bottom of the loop. The loop itself is too thin to see, but you do see cars moving on the cable with flashing aircraft warning lights. The guywires are also visible only as strings of flashing lights. Ecuador Station above is a white sliver appearing about half as long as the diameter of the full Moon.

Inside the Base, you get your seat assignment. The agent asks, "Viewing or nonviewing?" The walls of the cable cars are transparent, but some people can't stand heights, so portions of the walls can be opaqued. You say "Viewing" because you don't want to miss a thing. You go to the assigned gate and board your car. Each passenger car has three levels, and the floor plan is horseshoe shaped so that the cable can pass through the center of gravity.

After everybody is aboard, the hatches are sealed and the car is carried from the gate to the up tower. An elevator shoots you up, pressing you into the seat. The car's speed is matched to the cable's, and the car clamps on. As you rise at the sedate speed of 100 meters per second, a panoramic view of the Andes unfolds below. The sky deepens to

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purple and then black, but you can't see a stars because the glare of the Sun is t bright.

Thirty-three minutes later the car loose its grip on the cable, and gravity slows it t halt right at the bottom of Ecuador Static The Station's internal transport syste takes the car to an unloading gate.

It is still an hour until your railcar leav and you spend the time at a viewport. Th you board a passenger pod, which is lit more than a pressurized cylinder. The pod loaded onto a railcar, and you shoot out Ecuador Station like a bat out of Hell. Ir few minutes you reach orbital velocity, b you do not feel weightless because the car still accelerating rapidly. As your spe increases further, "down" seems to poi away from the Earth. The pod rotates 18 so you can still sit in your seat, and t railcar now seems to be hanging from t rail.

Through the window between your fe you see the low-to-high-orbit shuttle Galil approaching. Galileo is actually following highly elliptical orbit whose perigee is nea tangent to the Skyrail, but because you ha matched horizontal velocity, Galileo seer to be rising toward you from direct "below." At Galileo's closest approach, t railcar drops the pod and you are sudden weightless. Luckily, you have enough co trol of your nervous system that weightles ness is a pleasant feeling.

There is a reassuring thunk as Galil latches onto your pod. Because Galil never makes large velocity changes, mass

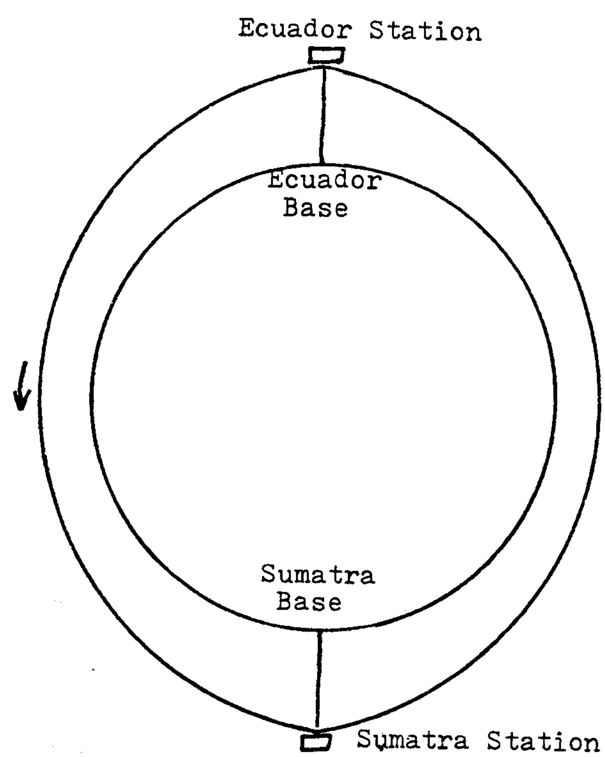

Figure 5. Two antipodal stations with skyrail following halves of elliptical orbits between them.

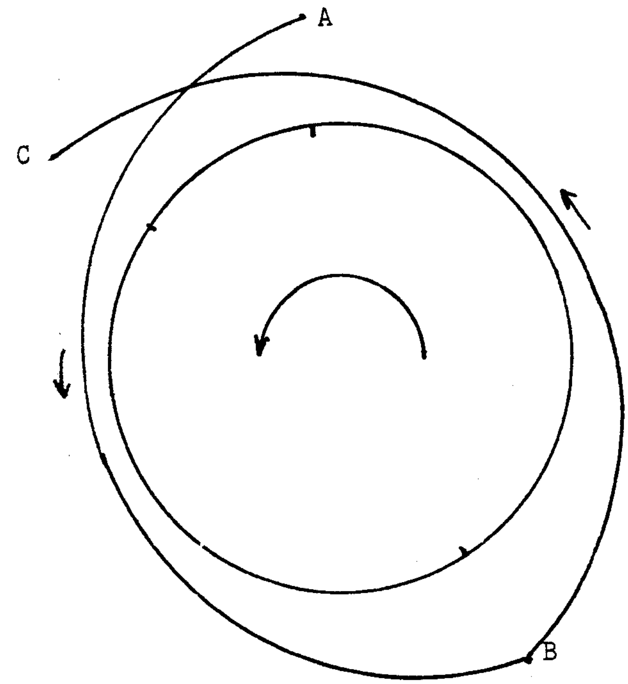

Figure 6. Orbits followed by piece of skyrail around rotating Earth.

not too critical and accommodations are semi-comfortable. For the next two days you have your own tiny cabin with its private zero-gee facilities.

Upon the nearing of Ceetee Habitat, you enter another transfer pod. Since the relative velocity of the shuttle and the habitat is about one kilometer per second, transfer is not as simple as it was back at the Skyrail. The end of a cable shoots out from the habitat and attaches to the pod. Galileo drops the pod, and the cable rapidly slows you as it unreels to its full fifty kilometer length. It takes an hour to reel in and dock. You are home!

Conclusion

Once built, a Skyrail system can be expanded. One rail can support several stations, as long as they are symmetrically placed. Embryo new stations could be built at the old stations, then moved into place and built up to full size. When a larger rail is needed, one perhaps ten times the size of the old one, it could be built in an orbit slightly inclined and slightly higher in order not to interfere with operations during construction. At change-over, the new rail would be pulled to exact zero inclination and the old rail carefully dismantled.

A Skyrail could easily handle the volume of traffic mentioned in the Introduction. A single station handling 100 passengers every 30 seconds would handle 100,000,000 passengers per year. By the year 2050 there could easily be more people in space than on the Earth.

To me, it seems that the role of the Skyrail in developing outer space may best be compared to the role of the railroads in developing the Great Plains. Before the railroads, travel was an adventure and a battle against the elements. Afterwards, settlers came in droves because the railroads provided access to eastern markets for their agricultural products. Now rocket travel is adventurous and expensive. With cheap and safe transportation such as the Skyrail provides, humanity can develop space to its full potential, and begin its reach for the stars.

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