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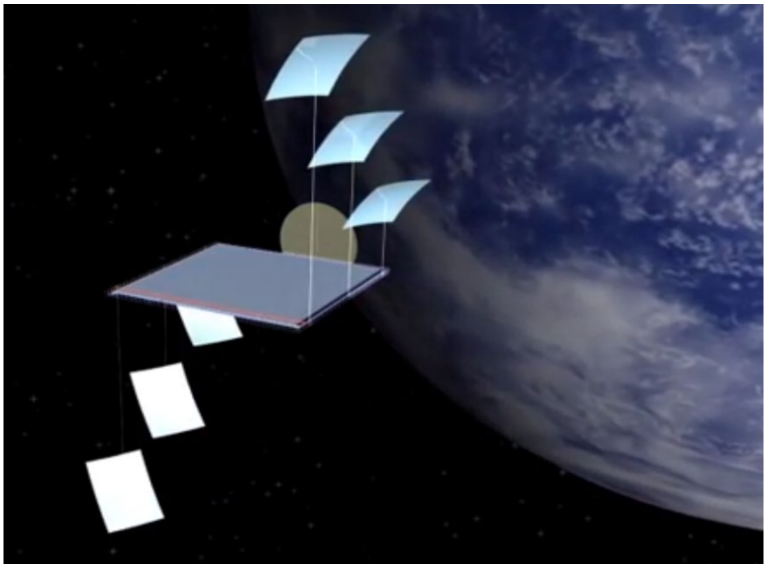

Space Transport for Power Satellites Beamed Energy Bootstrapping

Keith Henson and Anna Nestrova

ABSTRACT

This International SunSat Design Competition first-place winner for 2016 describes a beamed energy transport system that will operate in Space above low earth orbit (LEO) as a way to move power satellite parts into high orbits.

This design, entitled "Beamed Energy Bootstrapping," makes use of small propulsion power satellites to provide the energy for space-based vehicles using electric arcjets. The proposal lays out a scheme to get the first propulsion power satellite in place without damage as it passes through the orbiting space junk below 2000 km.

TECHNICAL BRIEF

Background

This new work builds upon a prior Thermal Power Satellite design that was a second-place winner in the 2015 Competition.

Even with advanced low cost vehicles, transport of power satellite parts to orbit is more than half the estimated cost for power satellites. The previous iteration of transportation concepts for power satellites incorporated high exhaust velocity, arcjet thrusters powered from an 8 GW ground station.

That design met, if marginally, the lift cost to GEO requirement of $200/kg or less for power satellites, an often-quoted figure that made economic sense. But the ground station design had problems. Its estimated cost was perhaps as much as $20 B, and installing such a transmitter would require flattening 110 square km of equatorial jungle. In addition, ground station utilization would be poor. In an initial 300 km orbit the vehicles could “see” the transmitter only 70 seconds every 90 minutes.

The New Design: The updated concept uses space-based propulsion power satellites (PPS) that operate at a much higher frequency to keep the antenna sizes reasonable. Two such satellites transfer 800 MW to the tug engines nearly full time.

Microwave diffraction-limited optics are linear with respect to distance and frequency. The standard 2.45 GHz power satellite design uses a 1 km transmitting antenna in space and a 10 km rectenna on the ground (10.6 km out to the first Airy disk minimum). Raising the frequency from 2.45 GHz to 25 GHz decreases the spot size by a factor of ten, down to a 1 km rectenna. Decreasing the distance by a factor of two shrinks the antenna to 500 m.

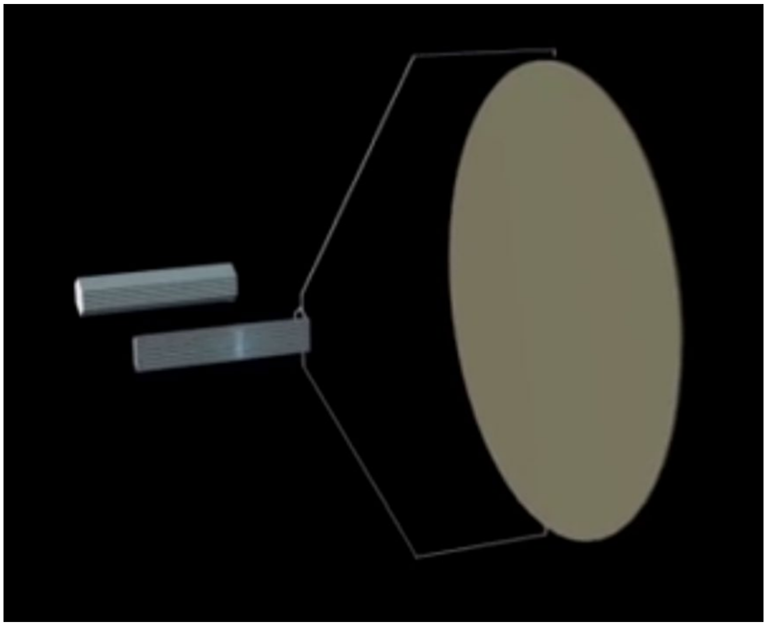

Figure 1: Cargo stack attached to 500m rectenna and tug

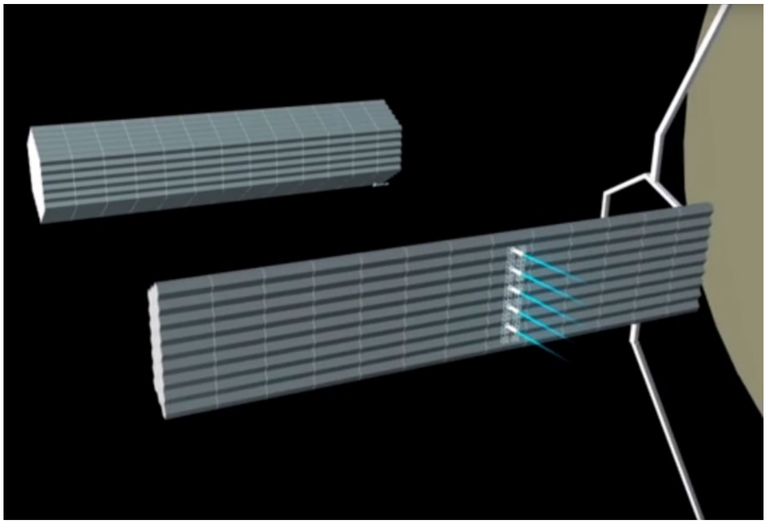

Figure 2: PPS powering tug

The follow-on problem is getting the PPSs on station. Even a small PPS has several square km of surface. It will not survive a long, slow trip through the space junk below 2000 km. (A full-scale power satellite takes about 40 hits.) The only solution the author could think of is to use high thrust chemical fuels to get above the space junk to where we can then construct the PPS.

The “kit” to build a 4000 ton PPS and the reaction mass to get it on station would fill 370 Skylon cargo containers. Hohmann transfer from 300 km LEO to a 2000 km orbit takes about 827 m/s delta V, split about evenly, 425 m/s for the first burn and 402 m/s for the second.

The fuel required for raising its orbit from 300 km to 2000 km is about 940 tons on top of the 4483 tons delivered to a 2000 km orbit. (The extra 483 tons are reaction mass for the PPS to self-power to its operating station at 18,000 km.) Compare this to the space shuttle that used about 730 tons of fuel (metric tons) to reach orbit. The three shuttle main engines (SSME) burned for 480 seconds, though not all of that was at the same fuel rate. For SSMEs, or similar rocket engines, the total burn time for both impulses would be ~620 seconds, about ten minutes, or about 5 minutes to enter the transfer orbit and 5 minutes to circularize. The Hohmann elliptical half orbit is close to an hour. For a Hohmann transfer orbit the accelerations are supposed to be impulses, but five minutes of burn out of an hour is close enough for this rough analysis.

At 2000 km, the “kit” is opened to begin constructing the PPS. The video illustrates the process of extracting a roll former and producing the frame and gantry, filling it with radiator tubes, paving two edges of the frame with concentrated PV modules, installing the transmitter and the mirrors that reflect light on the PV. Our design expects to temporarily fit out the transmitter stalk with arcjet engines used for a spiral transfer on out to 18,000 km. The stalk supplies power and cooling water for the arcjet engines. Depending on how many engines are used, the spiral trip out to 18,000 km could take from a few days to a few weeks. Once the PPS is on-station, its beam can power a tug.

While the first PPS is being constructed and moved out to station, a second stack plus a tug is assembled in LEO. The second stack contains parts for a second PPS, living quarters for the construction crew (based at 12,000 km), plus a 2000 ton tug plus thousands of tons of hydrogen reaction mass. When the first PPS is on-station and the stack is ready, we power the tug using the first PPS about half time. Depending on the mass of the second stack, it could take 30-60 days to reach the construction base at 12,000 km.

There, the second PPS will be constructed and sent out to 18,000 km, 180 degrees opposite from the first. During this time, parts for half of the first power satellite will be delivered to LEO along with a second tug. When the second PPS is on station, they will move two full 15,000 ton cargo stacks to the construction base every month.

ECONOMIC BRIEF

The basic economics of power satellites have been spelled out in numerous prior studies. In brief, to produce energy from space, the cost must be low enough (3 cents per kWh) to undercut electricity from coal. The cost per kg to GEO must be no more than \$200 for 6.5 kg/kW specific power. For ground-to-LEO using Skylon, the assumed cost is \$120/kg. That includes the cost of reaction mass delivered to LEO. For the previous model, the capital cost of ground microwave power, energy to run the transmitter, tugs and the cost of reaction mass came in just short of \$80/kg, making power satellites economical but by the thinnest of margins.

The estimated cost for the ground transmitter plus power plant was high – some \$16-20 B - and the operating cost for fuel to power it was substantial. The ground station could expect to take up some 110 square km.

This analysis assumes that the propulsion power satellites cost the same on a per kW basis as power satellites. Power satellites cost about \$1.2 B per GW of electrical output to the transmitter. Two of them are required, for a cost of \$2.4 B. The two PPSs supply 400 MW to the engines of two tugs. The tugs each raise 15,000 tons every 30 days, or about 1,000 tons per day for the pair. Rounding down, our rough estimate for the cargo flow to the construction site is 300,000 tons per year.

Assuming the cost of the two 2,000 ton tugs to be about the same per kg as the PPSs, the hardware cost of the transport system would be about \$3.6 B. Using a 5-year write-off of the hardware, the capital cost is about \$720 M/year or \$2.40

per kg, an absurdly small number in an aerospace context. The PPSs use free sunlight, so there is no fuel cost to power them.

The reaction mass is 20% of the cargo plus tug mass, so 15 kg of cargo takes ~4 kg of hydrogen reaction mass to move it to GEO (the location of the construction site makes no difference in the reaction mass total to GEO). The reaction mass cost per kg is $480/15 or $32/kg. That makes the total cost for getting power satellites to GEO around $150/kg. That figure is well under the $200/kg maximum permitted transport cost.

Business Plan

The author entered the PPS numbers into the economic model for a power satellite project in place of the previous ground station (see attached spreadsheet "Power Satellite business model construction rate with CO2 2016.xls.") As expected, the peak capital investment declined to $27 B, not considering the Skylon development cost. This number should be taken for what it is, the output of an unchecked spreadsheet. On the other hand, it could cost twice as much to get started and still be an economic winner.

Though the economics are important considerations, they seem less than decisive due to the scale of the project and the perceived risk. Previously, we talked about power satellites as a way to solve the energy crisis that would also deal with the buildup of CO2 in the atmosphere. The faster than expected rise in temperature and the rapid melting of glaciers is alarming governments around the globe.

Started soon and pushed hard, power satellites could displace fossil fuels rapidly enough to abort most of the projected climate change. The investment to reach the takeoff point where CO2 is rapidly reduced is much less than other proposals such as: "The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture."

Note: "For an installation cost of $2.74 trillion/yr over 10 years followed by a maintenance cost of $0.91 trillion per year, a network of direct atmospheric CO2capture plants could be emplaced that would be powerful enough to reduce global CO2 levels by ~50 ppm per decade . . ."
Robert Freitas' " Nanofactory Solution" estimate is more than 1000 times as much as this proposal.

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