Space Solar Power

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Project

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Abstract

Illustration 1: *Project Abstract*

Spacecraft and Orbital Parameters

Our spacecraft will consist of the following components:

A concentrating mirror with a total diameter of 5km (which is composed of several, smaller mirrors of around 20m diameter each). Each smaller mirror can be sent up individually. The mirror will focus sunlight onto the photovoltaic cells described below. Each spacecraft will have two concentrating mirrors.

A photovoltaic cell array about 3km wide, made up of many thin-film photovoltaic cells, will convert sunlight into electricity. The PV cell arrays can be sent up in 15-20 batches. Each spacecraft will have two photovoltaic cell arrays (one for each mirror).

A communications satellite component that will be in charge of monitoring the system and relaying information back to earth. This can be a run-of-the-mill comm. satellite, similar to the Milstar and Sirius satellites.

Transmission dishes will be set up in a virtual array of around 1km in diameter total (since the required size would be prohibitive for a single dish). These will be attached to the spacecraft in the shape of a ring. Each spacecraft will have two sets of virtual transmission dish arrays (one for each mirror - PV array).

And of course wiring will be required to run electricity from the PV cells into the transmission dishes and for running diagnostic information into the comm. satellite. The wires will be coated in foil in order to prevent them from heating in the sunlight (which will degrade their performance).

For the orbital parameters of the spacecraft, we will use a typical GEO (Geostationary Earth Orbit) with altitude 35,786km. Each spacecraft will be located along the equator, and their longitude location will depend upon which earth stations they are serving. More details about the earth stations will come later.

Transmission Parameters

We chose the frequency of 5.8GHz because it is currently an ISM band that could be allocated for our use. The frequency range around 2.4GHz is commonly used by radar systems on earth, and would also require much larger dish sizes to operate from GEO, therefore it was deemed less optimal. The downfall of the 5.8GHz range is that, since it is a shorter wavelength, it will attenuate much faster than its 2.4GHz counterpart. [11]

The typical usage for this band is short-range wireless communications (such as some LAN and Wifi products). Since these are only short range devices, and since our beam will be focused in a specific and (relatively) small area, they will see minimal interference from our actions. [11]

We can see from [12] that a satellite in GEO orbit would be in the sunlight the majority of the time, and would only be blocked for about an hour or so each night during the equinoxes (when the earth casts its shadow directly on the satellite). This means that the system will have minimal interruption periods from the sun. Since our earth stations are based in very arid regions of the earth, high power attenuation from humidity/rain will also be minimal.

According to [13], we can see that atmospheric heating due to the narrow-beam microwave would be minimal. The study says that fluctuations in the 2.4GHz band can cause temperature spikes that are more pronounced, but the fluctuations decrease as the frequency goes up. We can therefore assume that the 5.8GHz band would have much less fluctuations than the 2.4GHz band, and therefore less temperature spikes in the atmosphere. In order to completely ensure aircraft safety, we can enforce a no-fly zone around the earth-based harvesting stations. The energy is spread over such a wide area by the time it reaches earth's surface that any potential for physical damage (to living things or devices) should be minimal.

We can plot the dish gain using the programs provided in class. The image below shows the plotting (up to -60dB), which appears to be a perfectly straight line. This is because the half-power beamwidth is roughly $\tan^{-1}$(earth dish radius / distance to satellite) = 0.0015 degrees. The beam is so narrow and travels such a long distance that the side-lobes play no significant role in losses and interference.

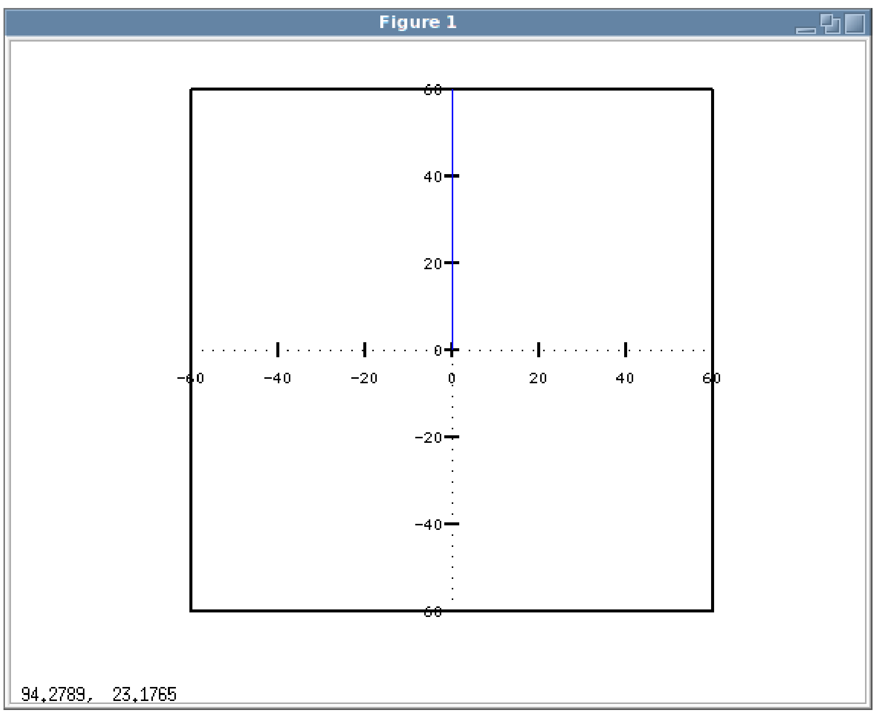


Image 1: *Side-lobe levels and taper*

Power transfer hardware

In order to make sure we are operating in the far-field, we want to ensure that $r > D^2 / \lambda$, so one can solve for $r > 2 * Ds^2 / \lambda$ to be well on the safe side. We chose a 5.8GHz signal, so we know that $\lambda = 51.72$mm. We also know that r is the altitude of the satellite, and since it is in GEO orbit we know this is about 35,786km. Solving for Ds, we get Ds < 961.99m.

Likewise, we can figure out the size of the earth-based dish by using the formula $Ds*De = r* \lambda$, which gives us De = 1.93km.

Using the software provided in class, one can determine the optimal way to send power to the earth dish with a space dish 961m in diameter (constructed from a virtual array). By using thirteen dish antennas (1m each) in an array 961m in diameter over an area of 5km x 5km the power density output can be seen below:

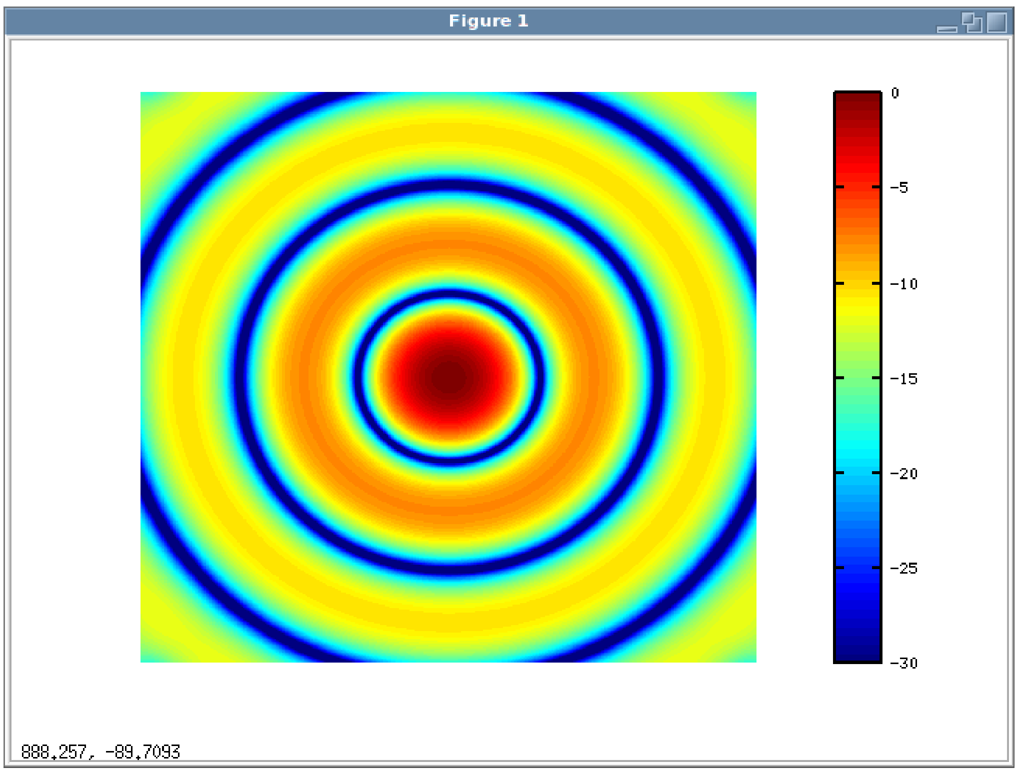


Image 2: *Harvesting array footprint on earth, 5km x 5km*

And below, the same thirteen dish antennas in an array 961m in diameter with receiving earth station 1.93km in diameter (1.93km x 1.93km), zoomed in.

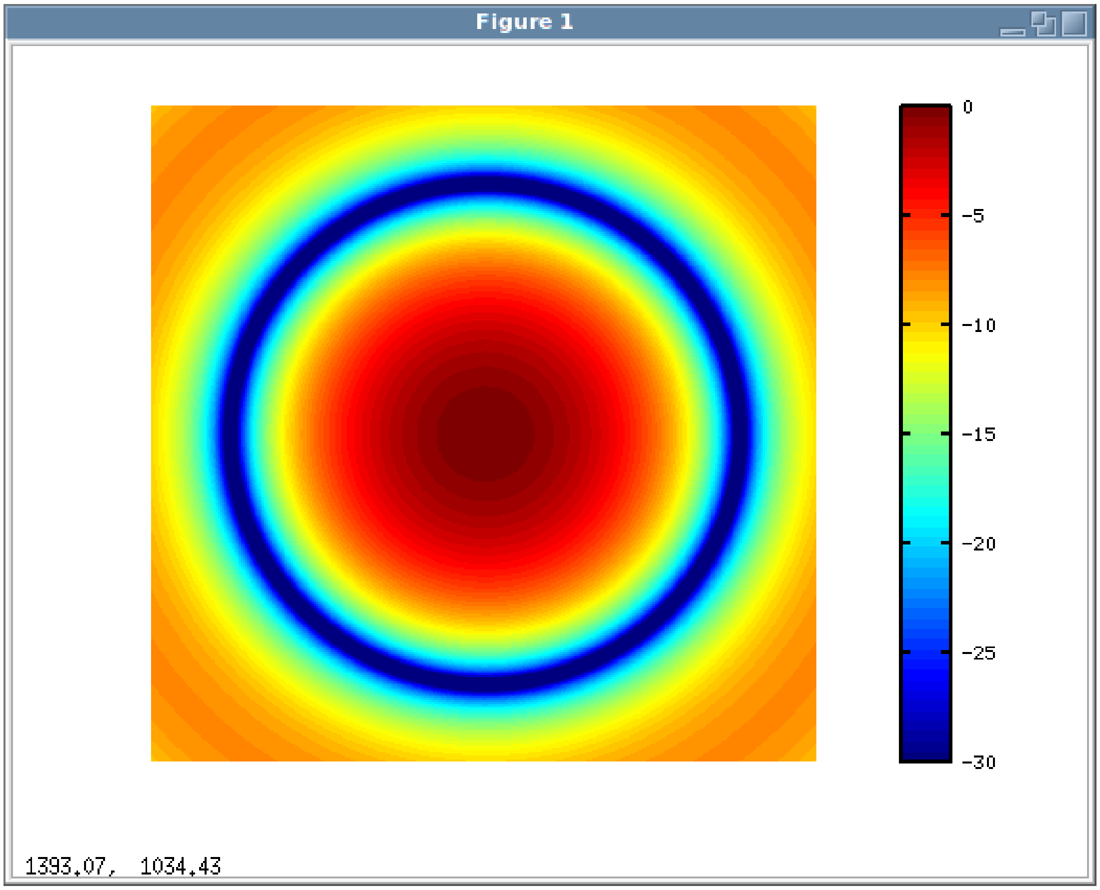


Image 3: *Harvesting array footprint on earth, ~2km x 2km*

Comparing the two, we can see that most of the energy is put into the ~2km x 2km earth antenna area, while some residual energy is wasted outside the earth dish area (though most of it is less than -10dB).

Earth-harvesting antenna design

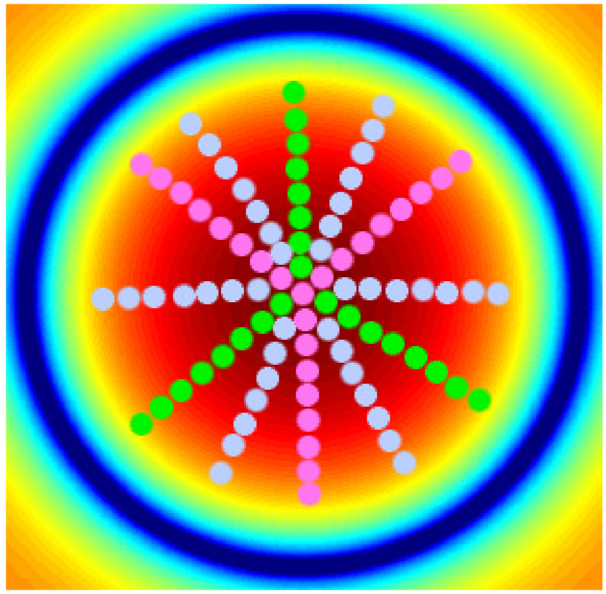


Image 4: *Antenna array coverage example*

The receiving antennas at each earth station, as specified in the previous section, will need to be 1.93km in diameter. Of course this is not feasible for a single dish antenna, therefore the receiving antenna will be made up of an array of antennas. Each antenna in the array should be roughly 25 meters in diameter (these are pretty large!), and in total they should optimally cover much of the 6 square kilometers of space.

The array should contain at least 80 antennas in a Y-shape, though upwards of 3000 such antennas in a star pattern would be optimal for best power collection (filling most of the 1.93km diameter dish array). In the image above, one can see an example layout with a moderate number of dishes (but coverage is still lacking). If building in an area difficult to get to, however, it may be cheaper to use 3 million dishes that are 1 meter in diameter each (though still following the scheme described above).

The project specification says that the cost of building this collection array will be taken up by the local companies involved in the power grid, and so are not considered as part of the project budget (though the project details that it would cost around $1 billion for a 5 GW harvester).

End-to-end conversion efficiency

Link budget calculation:

R_{geo} = 35,786km
Rs = Ds/2 = 961m/2 => 480.5m
Re = De/2 = 1.93km/2 => 965m
Pt = 5 GW => 96.99 dBw

Assume perfect antenna efficiency
$Gt = (4\pi/ \lambda^2) * (\pi*Rs^2)$ => 95.3243 dB
$Gr = (4\pi/ \lambda^2) * (\pi*Re^2)$ => 101.381 dB

$Pr = Pt + Gt + Gr + 20*\log(\lambda/4\pi) - 20*\log(Rgeo)$
=> Pr = Pt + Gt + Gr – 47.711 dB – 151.074 dB
=> 94.9103 dBw => 3.1 GW

Even under optimal conditions (perfect antenna efficiency and only typical path losses) we see that we only have a link-budget based efficiency of 62%. Even with hundreds of antennas in our earth station collection array, we would be lucky to retrieve 1 GW of power out of the 5 GW that was sent to earth (1 GW is assuming 60% efficiency of the setup).

For this project, we will assume that the harvesting arrays are nearly perfect, meaning that they cover the power area well enough to collect the majority of the power. I made this assumption because the cost of the earth-based harvesting arrays are not part of my project costs, and so they can be expensive without affecting my power supply rates.

Space-hardening / Resiliency

The biggest point of failure in the design will most likely be the concentrating mirrors, since they have a surface area of 39.3 km^2. This is quite a large target for micrometeorites to hit (it is over 15 square miles!), and it is likely they will shatter upon impact. This will ruin the efficiency of the system, since sunlight will not be collected onto the photovoltaic cells as efficiently. This can be mitigated by covering the glass with a protective coating, at the very least to prevent shattering. Dust collecting on these mirrors will also reduce their efficiency over time, but much more slowly.

The next most likely point of failure will be the photovoltaic cells, whose total area makes up 14.14 km^2 (over 5 square miles). Again these may be impacted by micrometeorites, lowering the efficiency of energy conversion. Likewise, the solar cells themselves have a relatively short lifespan, and so they will need to be replaced every 20 - 30 years [10], even without micrometeorite impacts.

The communications electronics will be kept within the communications satellite, and so they will be protected from most hazards (such as micrometeorites and radiation). The wiring that connects everything together is covered in tin foil to prevent it from being warmed up by sunlight, and is about 2mm thick. Because of its small size it is not likely to be significantly impacted by micrometeorites.

Budget and timeline

The overall launch cost for a Generation 2 (G2) launch is $100/lb, and the overall launch cost for a Generation 3 (G3) launch is $50/lb. We will assume that the cost of the transmission dishes and wiring components will be negligible (since they are much cheaper and lighter than the other costs, as we will see).

Labor and supplies costs for the overall project (not including per part costs, which are shown below) will be on the order of millions of dollars, but is negligible compared to the billions of dollars that the project will cost in total (per 5 GW harvester).

Photovoltaic Cells

Using the thin-film PV cells described in the project, we know that the cells are capable of producing 16.8 Kwatts/Kg. We need our arrays to produce 5GW each, which translates to 5GW * (kg / 16.8kW) => 297,619 kg of PV cells (or 656,138 lbs) per array.

For a G2 launch, we can estimate the total cost will be roughly $100/lb * 656,138lb => $65.6-million per array. For a G3 launch we can estimate it to be $50/lb * 656,138lb => $32.8-million per array.

Each PV array is specified to be 3km across (radius 1.5km), meaning we need 14.14 km^2 of PV cells to make up each 3km PV array. With costs taken from [3], we can estimate that thin-film PV technology will cost around $50-million per square kilometer ($50/m^2), which equates to a total of 14.14 km^2 * $50-million /km^2 => $706-million per array.

Summary cost for PV cells (per array)

Materials/labor cost	$706-million
Launch cost (G2)	$65.6-million
(G3)	$32.8-million

Mirrors

Each concentrating mirror set is specified to have a diameter of 5km, so we need an area of about 39.3 km^2 of mirror, or 423-million square feet.

Based on weights seen from [1], we can estimate that a 1/8" thick mirror will weigh about 1.6 lbs / square-foot. We can quickly calculate that the total weight of mirrors needed will be roughly 1.6 lbs/sq-ft * 423-million sq-ft => 676.8-million lbs.

For a G2 launch, we can estimate that it would cost (in total) around $100/lb * 676.8-million lbs => $67.68-billion. For a G3 launch, we estimate $50/lb * 676.8-million lbs => $33.84-billion.

In terms of materials costs, we can guess that a standard mirror costs maybe around $5 per square foot (the mirrors do not need to be telescopic-grade). This works out to be about $5/sq-ft * 423-million sq-ft => $2.115-billion for the total concentrating mirror set.

Summary cost for concentrating mirrors (per array)

Materials cost	$2.12-billion
Launch cost (G2)	$67.7-billion
(G3)	$33.8-billion

Communications Satellite

Based on impirical data, we can see that communications satellites typically weight somewhere around 3,000 kg (or 6,614 lbs) [4]. In terms of launch costs this proves to be negligible, since a G2 launch would cost $100/lb * 6,614 lbs => $661.4k. Likewise, a G3 launch cost would be around $50/lb * 6,614 lbs => $330.7k.

The cost of developing and building the satellite is much more, however. Based on the cost of a Milstar satellite [5] and the Sirius satellite costs [6], we can estimate that building the communications satellite (including labor costs, etc.) that would coordinate communications with our space harvester should cost up to around $500-million.

Summary cost for communications satellite (handling 2 arrays)

Production/labor cost	$500-million
Launch cost (G2)	$661.1k
(G3)	$330.7k

Global Energy Needs

We can estimate that each "node" (2 mirror arrays, 2 PV arrays and a comm. satellite) can generate 10GW of power (5GW per array). Considering that there are 438,290 hours in a year, we can calculate that each node is capable of producing around 10GW * 438,290 hrs/yr => 4,383TWh of power each year.

Based on data collected from source [9], we can estimate the following power (and node) requirements:

Year	Power Need	Nodes required
	Global	
2008	20,183 TWh	4.6+
2020	27,400 TWh	6.3+
2035	35,300 TWh	8+
	China	
2008	9,000 TWh	2+
2020	11,000 TWh	2.5+
2035	11,000 TWh	2.5+

India		
2008	5,000 TWh	1+
2020	6,000 TWh	1.4+
2035	6,000 TWh	1.4+

All other countries had power requirements that were 3-4,000 TWh or less.

The first 8 downlinks were specified to need a power cost ($/kWh) as seen below:

Country	Years 1-6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12+
Central Europe	26¢	23.4¢	21.3¢	19.6¢	18.2¢	17.1¢	16.3¢
Japan	22¢	19.8¢	18¢	16.6¢	15.4¢	14.5¢	13.8¢
Mexico	20¢	18¢	16.4¢	15.1¢	14¢	13.2¢	12.5¢
West Virginia	19¢	17.1¢	15.6¢	14.3¢	13.3¢	12.5¢	11.9¢
Georgia	12¢	10.8¢	9.8¢	9¢	8.4¢	7.9¢	7.5¢
TX, SA, China	11¢	9.9¢	9¢	8.3¢	7.7¢	7.2¢	6.9¢

This means that our system needs to be able to supply power to sites (for instance) in China, Texas and South America for 6.9¢/kWh after 12 years (or 11¢/kWh for the first 6 years).

Assuming that the lifetime of our satellite system is only about 12-15 years (though it is likely to be much, much longer), we can determine the cost per kWh based on the total cost for both launches (G2 and G3) for *each 5 GW array set*.

G2 launch	$71.07-billion / (5GW * 12yrs * 8,766 hrs/yr)	13.5¢ / kWh	12 year lifetime
	$71.07-billion / (5GW * 15yrs * 8,766 hrs/yr)	10.81¢ / kWh	15 year lifetime
G3 launch	$37.2-billion / (5GW * 12yrs * 8,766 hrs/yr)	7.07¢ / kWh	12 year lifetime
	$37.2-billion / (5GW * 15yrs * 8,766 hrs/yr)	5.66¢ / kWh	15 year lifetime

The total space system, consisting of 4 satellite nodes, is 4*(2*PV + 2*mirror + comsat), which comes out to be around $283.3-billion for two G2-launched satellite nodes and $147.8-billion for two G3-launched satellite nodes ... about **$431-billion total** (and almost **$1-trillion** for all 8 satellites). As mentioned before, this figure does not include the earth harvesting arrays, covered by other companies.

As mentioned before, the additional, overall labor and supplies costs (project development, organization, logistics, etc.) might come out to around $500-million (about 800 workers for 13 years of labor at $50k/yr), which is negligible in terms of hundreds of billions of dollars.

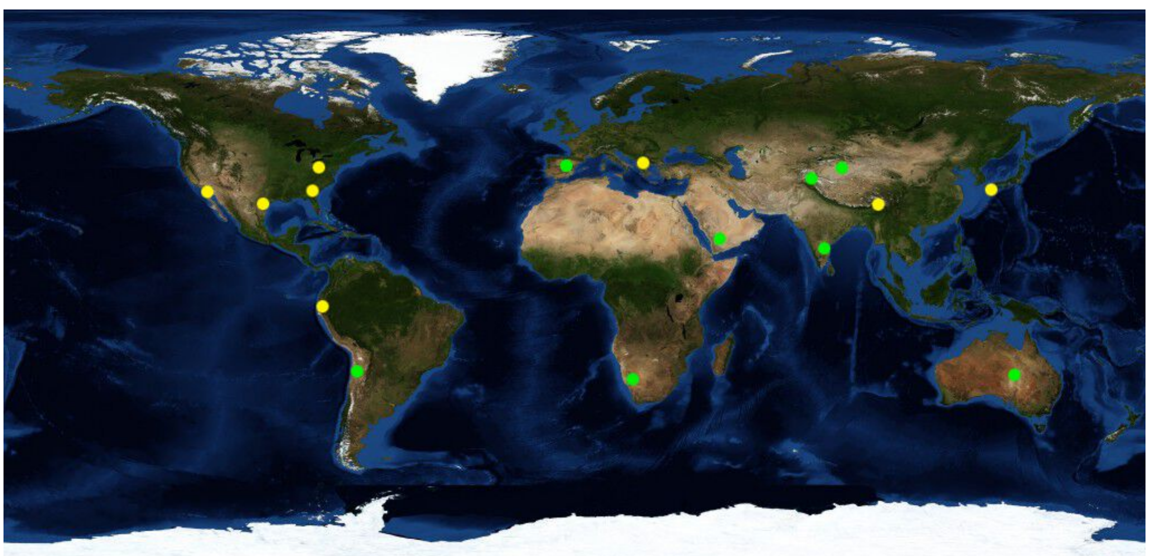
Timeline

As specified, all satellites launched after 5 years will be considered G2 and all satellites launched after 10 years will be considered G3. We have 13 years to get the first 4 satellite nodes (servicing 8 downlinks) up and running (by 2025). We have 16 years (3 more years) to get the next 4 satellite nodes up and running (by 2028).

If we spend 5 years developing the systems and then launch two (G2 launched) satellites for 5 years after, then we can launch the other two (G3 launched) satellites after that. This will give us two G2-cost satellites and two G3-cost satellites running. The G2 satellites will be ready within 10 years (5 years developing + up to 5 years launching), and the other two will be ready shortly after (within 3 years). This means we can get all of the satellites up in the air within our 13 year deadline. We can then launch 4 more satellites using G3 technology within 3 years to meet our goal of eight total satellites by 2028.

Assuming a 15-year lifespan, we can easily supply power for 4 sites for 10.81¢ / kWh (using the G2-launch satellites), and we can supply power for the other 4 sites for 5.66¢ / kWh (using the G3-launch satellites). How we assign satellites to downlink sites is irrelevant in terms of user cost, since the budget for the project will be divided among all satellites in the end, anyway.

Satisfying Global Energy Needs



Map 1: *Downlink locations displayed on a map (taken from [8]).*

On the map above, the locations marked in yellow are the first round of 8 downlinks (given in the project specification), scheduled to be completed by 2025. The locations marked in green are the second round of 8 downlinks (strategically chosen by me), scheduled to be completed by 2028.

I have chosen to pair up downlink sites based on how close they are longitudinally-speaking (since the satellites are in GEO orbit, they will be around the equator, and the important aspect here is their longitude along the equator). Each satellite node can service two downlink sites, so each pair of sites will share a satellite.

My initial pairings (for the first 4 satellites) are:

- Central Europe and China
- Japan and Mexico
- Georgia and West Virginia
- Texas and South America

After the launch of the next 4 satellites, they can be re-paired:

- Japan and Australia
- Mexico and Texas
- West Virginia and Georgia
- South America (both sites)
- Spain and South Africa
- Greece and the Middle East
- 2 x India-China location pairs (4 sites)

With two satellite nodes (4 downlinks) servicing India and China, this will give them 9,676 TWh of power each year. Between the two, they will need 17,000 TWh by 2035 [9], and this will provide them with more than half of their energy needs (one of the goals of the project).

The energy requirements of the remaining countries is much less than that of India and China, and the given downlinks should satisfy most of their energy needs.

Communications systems

The communications antenna will be a simple dish antenna using a general bent-pipe transponder. Given information from source [7], I decided to go with a carrier frequency of 5.8GHz, and therefore a bandwidth of 150MHz (frequencies 5.725GHz to 5.875GHz are allocated). We should not have to worry about interference from the harvested energy beam (which is also using 5.8GHz) because the communications beam will be required to be sent to a different area on the earth than where the harvested energy is being collected.

Based on the Faraday rotation taught in class, we know that a 5.8GHz signal will rotate less than 12° through the atmosphere. Using an 8-ary PSK (Phase Shift Keying) modulation scheme, each code will be separated by 45° (22.5° in both directions). This is well within the tolerance, given an atmospheric 12° rotation possibility. This will also allow us to use a cheap amplifier because we do not need to worry about corruption due to clipping (it is phase-shift keyed).

For security purposes, I have chosen to use CDMA (Code Division Multiple Access) for communications to the satellite systems. With CDMA, our pseudo-random sequence can be kept a secret to only those who need to communicate with the satellites (and each satellite can have a separate pseudo-random sequence). We can even encrypt the sequence with another sequence for added protection. This ensures that only people who know the sequence are able to read from (and send messages to) each satellite. Using CDMA also protects us from jamming, since a jammer would need to blast high-energy EM radiation over 150MHz of bandwidth in order to stop communications with the satellite.

Conclusion

In the end, we can see that we are capable of producing a set of eight satellite nodes by 2028, sending five GW of power to 16 harvesting stations on earth. Likewise, we can readily get a working constellation of four satellite nodes up and running by 2025.

For the 2025 projections, with two G2-launch nodes and two G3-launch nodes, and assuming a system lifetime of at least 15 years, we can easily meet the specified power costs for the first eight sites. Spreading the project cost out over 15 years, we can easily supply power for four sites for 10.81¢ / kWh, and we can supply power for the other four sites for 5.66¢ / kWh.

Based on this, we can come up with the following (minimum) pricing policy ($/kWh):

Country	Target cost	Minimum cost	Marketable cost	Profit
Central Europe	16.3¢	10.81¢	15.10¢	4.29¢
Japan	13.8¢	10.81¢	12.80¢	1.99¢
Mexico	12.5¢	10.81¢	11.50¢	0.69¢
West Virginia	11.9¢	10.81¢	11.10¢	0.29¢
Georgia	7.5¢	5.66¢	6.70¢	1.04¢
TX, SA, China	6.9¢	5.66¢	6.62¢	0.96¢

Even taking into account that only about 3 GW of power makes it to the harvesting arrays on earth (60% efficiency), if we project the lifetime of the system out to 25 years (which is reasonable), then we can make these same cost guarantees. This is because the 60% efficiency and 60% lifespan increase cancel each other out in the power cost calculations.

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