Space Solar Power: A Flawed Concept

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ECE 6390

Fall 2011

Introduction

Space solar power has been put forth in this class as a desirable, achievable, way to harvest Gigawatts of solar power from space [1][2][3][4]. This power would in turn be “gently” [1] beamed to Earth to provide baseload power for the power grid. What will be put forth here is that:

- Photonic pressure renders GEO-based SSP impractical.
- Excessive transmit dish sizes render GEO SSP impractical.
- Steering the transmit dish 1-2 beamwidths per second renders MEO too risky.
- Power densities at the transmit dish surface will melt or bend it out of shape.
- Practically sized dishes must be in the millimeter wave, with severe penalties for rain fade and surface tolerance.
- Being forced to MEO requires an expensive constellation to guarantee nighttime power.
- Simulations with real-world data reveal a minimum 2/3 chance, per beam, per day, of frying a LEO satellite below you.
- Requires massive (50 nautical mile), unrealistic no-fly zones around the ground stations: no eligible locations in South Georgia or South Texas.
- Involves power densities 10-100 times FCC and internationally accepted standards. The consequences of accidental exposure are dire.
- 24/7 baseload power would not be available due to excessive rain fade at millimeter wave, worker safety during rectenna inspections and repair, insufficient constellations, and ensuring the safety of LEO satellites.

Chapter 1: Photonic pressure at GEO/MEO

The solar intensity, I_0 , in earth orbit is about 1361 Watts per square meter [5][6]. A basic, thermodynamic reality of SSP is that if you want X watts of power, you have to collect *at least* (X/ I_0) square meters of solar radiation. This is a *minimum* cross-sectional area the spacecraft presents to the sun. However clever, novel, unique, or complex your design, this is a reality of thermodynamics which cannot be cleverly sidestepped.

The problem is, those same photons which provide you "free" energy are also applying a gentle pressure against the cross-sectional area of your spacecraft. This pressure can be calculated by the elegant formula [6][7]:

$$P = \frac{I_0}{c} = 4.54 * 10^{-6} \quad \frac{Newtons}{m^2} \tag{1-1}$$

Where c is the speed of light. This is a slight pressure, to be sure, but becomes quite sizeable when your cross-sectional area is measured in square kilometers. This value is actually the best case scenario, where photons are absorbed. The pressure is slightly less than *twice this amount* if the photons are reflected [6][7]. This would be the case for the large mirror array of the Symmetric Collector [1].

What are some typical values? A design which collects 10 Gigawatts of solar energy must have, at bare *minimum*, a cross-sectional area of:

$$Area = \frac{10 * \ 10^9 \ W}{1361 \ (\frac{W}{m^2})} = 7.35 * \ 10^6 \ m^2 \tag{1-2}$$

The photonic force will be, at bare *minimum*:

$$Force = \left(4.54 * 10^{-6} \frac{N}{m^2}\right) * (7.35 * \ 10^6 \ m^2) = 33.4 \, Newtons \tag{1-3}$$

Which is roughly equal to what 8 pounds feels like at sea level. Remember this figure uses the absorption pressure. If the satellite has reflective arrays, the force will be close to *double*.

The acceleration that occurs will be this force divided by the spacecraft mass. In this case, the more mass the better, to minimize the acceleration caused. Let's assume a humongous spacecraft of 400,000 Kg (roughly the mass of the ISS) [8]. The resultant acceleration will be:

$$a_{photonic} = \frac{33.4\ N}{400000\ Kg} = 8.35 * \ 10^{-5}\ m/s^2 \tag{1-4}$$

For lighter spacecraft, the acceleration will only be worse. This seems like a tiny amount. Does it even matter? In GEO it does.

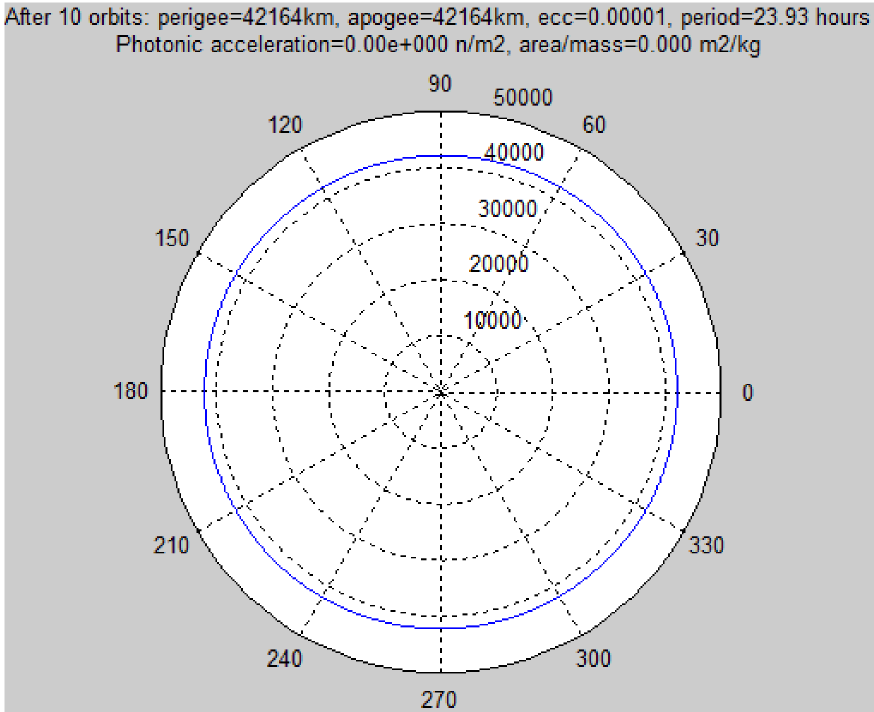
The Earth's gravity drops off dramatically. At GEO, an altitude of 35784 km, it is only 2% as strong as at the surface. The following table, calculated from first principles, illustrates this:

Notes	**Altitude (km) above Earth**	**Acceleration due to Gravity (m/s^2)**
Sea level	0	9.8
Typical LEO	500	8.4
Max LEO	1500	6.4
MEO; 10x stronger than GEO	7000	2.2
GNSS (GPS, GLONASS)	20000	0.57
GEO	35784	0.22

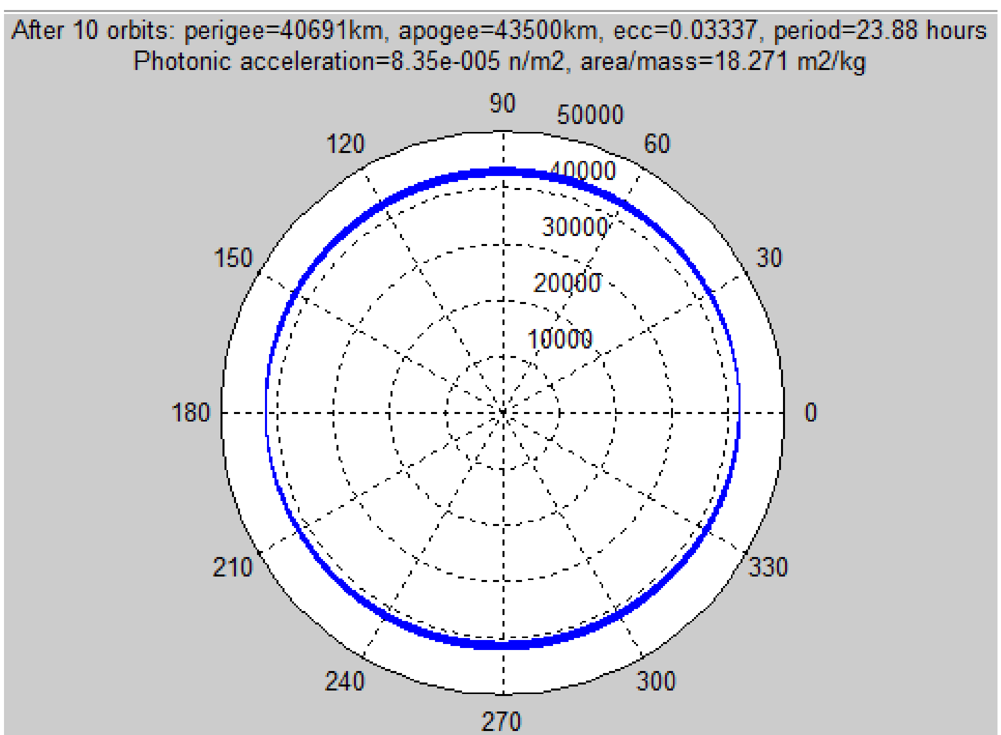
Is Earth's gravity so feeble at GEO, that even this very slight force can knock our SunSat out of orbit? A MATLAB simulation was performed [9].

On the following page are 10-orbit tracks. The top orbit is the "control", which is a standard GEO orbit with no perturbation due to photon pressure. The bottom is the same simulation with the above acceleration applied. In this simulation, the sun starts in the "180" position, on the left. Thus, the sunshine is flowing from the left, to the right. The simulation slowly moves the sun's position counterclockwise, to match the Earth's orbit around the sun. This is merely a 10-orbit (~10 sidereal day) simulation, but the results are stark.

The SunSat's orbit, in just 10 days, has flattened to an eccentricity of 0.033. Its perigee is down to 40691km and apogee up to 43500km. Its period has been shaved down to 23.88 hours from a normal 23.93 hours. All 10 orbits are on the same graph. The "smearing" effect shows graphically how the orbit flattens with each successive orbit.



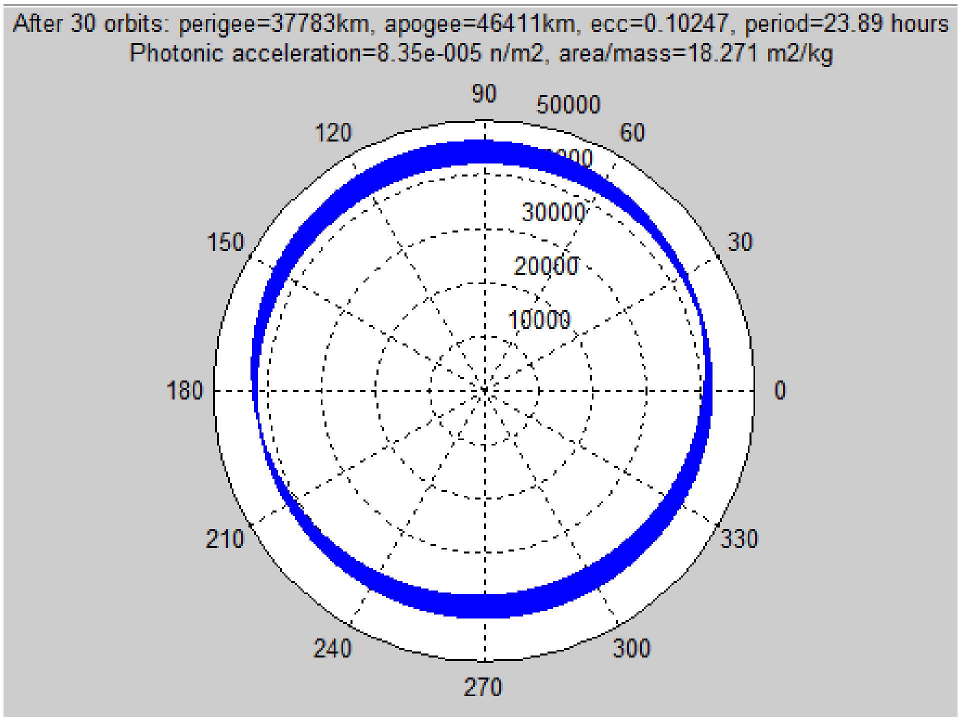
CONTROL: A boring satellite in GEO orbit. No photonic force. 10 orbits.



SunSat with previously described acceleration due to photonic pressure. 10 orbits.

The station keeping requirements for this SunSat would be prohibitive and unreasonable. Daily burns would be needed to keep it in the correct orbit. Fuel would have to be continuously ferried to GEO orbit to replenish its supply.

For further amusement, here is what happens after 30 orbits:



SunSat orbit: severely distorted after 30 orbits

After a month in GEO, the SunSat is now flying thousands of kilometers above and below its assigned GEO slot, with an eccentricity now exceeding 0.100 .

What about making the satellite smaller? It won't make a bit of difference! Consider the following:

The force applied to the SunSat is its cross-sectional area times I_0/c. Further, the acceleration is this force divided by the spacecraft mass.

$$a_{photonic} = \frac{area * \frac{I_0}{c}}{mass} \tag{1-5}$$

We rearrange as:

$$a_{photonic} = \left(\frac{area}{mass}\right) * \left(\frac{I_0}{c}\right) \tag{1-6}$$

And observe the acceleration does *not depend on the area or the mass alone, but rather, the ratio of the two*. If the bulk of the satellite's mass is solar collection, then mass is roughly proportional to collector size. Scaling the SunSat bigger or smaller will not affect this ratio.

Consequently, if a different SunSat has half the surface area receiving pressure, but half the satellite mass, the acceleration will be the same. This is reflected in the "area/mass" ratio of the above graphs.

So what area/mass ratios, and their equivalent photonic accelerations, are acceptable at GEO? From the web site "celestrak", an examination of GEO satellites [10] found most all have eccentricities below 0.0005. The standard was used of an eccentricity of no more than 0.0005 after 30 orbits (~ 30 days) as "acceptable".

The same MATLAB simulation was performed at GEO, for reduced photonic accelerations, until an acceptable result was attained. At an acceleration of $4 * 10^{-7}$ m/s^2, after 30 orbits, eccentricity was down to 0.00049. Dividing this acceleration by (I_0/c) yields a maximum area-to-mass ratio of 0.088 m^2/kg.

Thus, <u>photon pressure imposes a severe constraint</u> on placing SunSats in GEO orbit. The following table summarizes this, based on the constraint of 0.088 m^2/kg.

For a SunSat of mass: (kilograms)	**Maximum cross-sectional area & power collection based on 0.088 m^2/kg**	
	Maximum cross-sect. area presented to sun (m^2)	**Theoretical *maximum* collection (I_0=1361 W/m^2) (Megawatts)**
1,000	88	0.12
10,000	880	1.20
100,000	8800	12.0
1,000,000	88000	120.0
10,000,000	880000	1200.0

Even to break 1 Gigawatt of solar input, the SunSat would have to have a mass of 10 million kilograms to get the photonic acceleration down to an acceptable level. This is obviously impractical. The conclusion here is that <u>photonic pressure renders GEO-based SunSats wholly impractical.</u>

What about MEO?

Photonic acceleration may present less of an issue at MEO. First, Earth's gravity is stronger than at GEO, so photonic acceleration should have less effect. Also, the population at MEO is much less than GEO, so we can be less strict about maintaining precise orbits.

In the earlier table of gravitational attraction at various altitudes, it was noted that Earth's gravity is ten times as strong at an altitude of 7000 km than at GEO. The simulation was repeated at this altitude for 30 days. At this orbital period (4.28 hours), this encompasses 168 orbits. Higher and higher photonic accelerations were tested, to see where it would become intolerable.

The following table summarizes the eccentricity, perigee, and apogee, for various photonic accelerations at an initial orbital altitude of 7000 km.

Photonic acceleration		**Orbit shape after 30 days (168 orbits)**		
m/s^2	**Equivalent area/mass ratio (m^2/kg)**	**Eccentricity**	**Perigee Altitude, km**	**Apogee Altitude, km**
$4 * 10^{-6}$	0.875	0.00277	6963	7037
$4 * 10^{-5}$	8.75	0.028	6624	7374
$4 * 10^{-4}$	87.5	0.277	3289	10691

Even an area/mass ratio of 8.75 is right on the cusp of creating an unstable orbit. If we go ahead and accept this, because we are less strict about maintaining precise orbits here, we get:

For a SunSat of mass: (kilograms)	**Maximum cross-sectional area & power collection based on 8.75 m^2/kg**	
	Maximum cross-sect. area presented to sun	**Theoretical collection (I_0=1361 W/m^2) (Megawatts)**
1,000	8,750 m^2	11.9
10,000	87,500 m^2	119.0
100,000	875,000 m^2	1,190.0
419,400	3.67 km^2	5,000.0
840,000	7.35 km^2	10,000.0

With a station roughly equal to the mass of ISS, we could theoretically harvest 5 GW; for a station twice as massive, the goal of 10 GW might be met. These numbers seem encouraging on the surface. As we will see later, they come with 2 pyrrhic tradeoffs. First, a constellation of SunSats must be maintained. Second, the beam must be dynamically steered from orbit to ground.

Lowering the SunSat's orbit more would further reduce the impact of photonic pressure; however, as the next chapter will show, it would be difficult or impossible to provide continuous power at night.

Summary

Photonic pressure at GEO orbit places fatal constraints on the size of satellites which can be put there. By going to lower MEO orbits, the effect of photonic pressure is diminished. In the following chapters, the heavy tradeoffs this demands will be examined.

End Notes

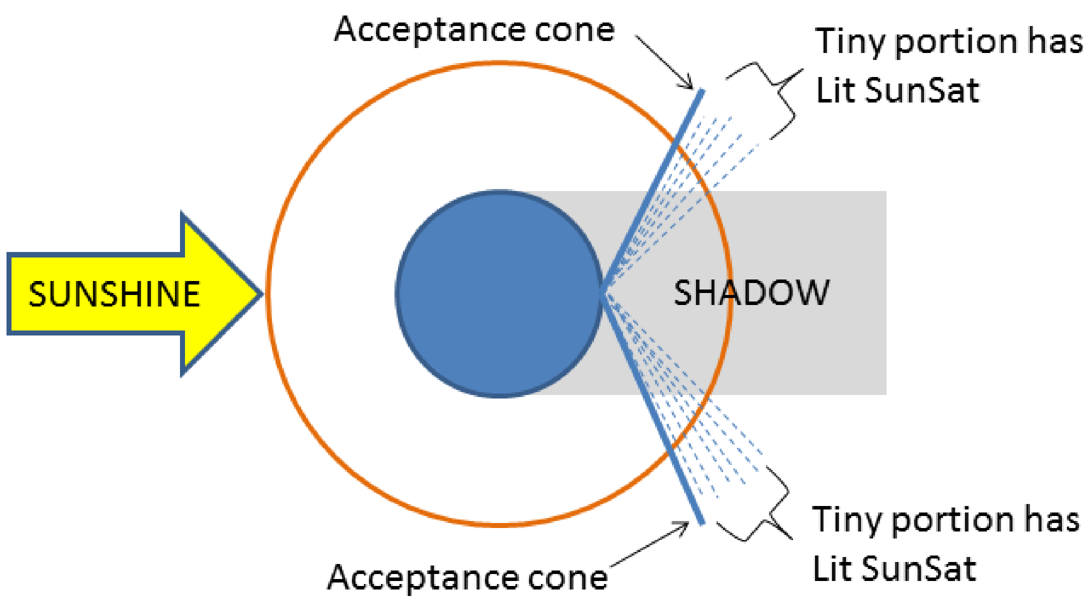
1. Space Solar Power Institute. "Space Solar Power Institute – Clean Baseload Energy." Internet: www.solarsat.org [Nov 2011].
2. D. Preble. ECE6390. Class Lecture, Topic: "Sustainable Energy for Many Tomorrows." Georgia Institute of Technology, Atlanta, GA, Sep. 15, 2011. Available: http://streaming1.ece.gatech.edu/research/labs/propagation/ECE6390/notes/video/Lecture110915/ece_6390_20110915.wmv, [Nov 2011].
3. N. Komerath. ECE6390. Class lecture, Topic: "The Space Power Grid Approach to Space Solar Power." Georgia Institute of Technology, Atlanta, GA, Sep. 9, 2011. Available: http://streaming1.ece.gatech.edu/research/labs/propagation/ECE6390/notes/video/Lecture110908/ece_6390_20110908.wmv, [Nov 2011].
4. G. Durgin. (2011, Sep.) *Satellite Communications Class Project: Space Solar Power* [Online]. Available: http://www.propagation.gatech.edu/ECE6390/project/Fall2011/SatCom_Project_2011.pdf [Nov 2011]
5. G. Kopp, J. Lean. (2010, Oct) "A new, lower value of total solar irradiance: Evidence and climate significance." *Geophysical Research Letters* [Online] , Vol. 38, L01706. Available: http://www.agu.org/pubs/crossref/2011/2010GL045777.shtml [Nov 2011]
6. Wikipedia. "Radiation Pressure." Internet: http://en.wikipedia.org/wiki/Radiation_pressure [Nov 2011].
7. O. Montenbruck, G. Eberhard. (2000) "Solar Radiation Pressure" in *Satellite Orbits: Models, Methods, and Applications.* (1st edition). [On-line]. pp 77-79. Available: http://books.google.com/books?id=hABRnDlDkyQC&lpg=PA77&dq=radiation%20pressure%20photon%20orbit&pg=PA77#v=onepage&q&f=false [Nov 2011].

8. NASA. “International Space Station. Facts and Figures.” Internet: http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html [Nov 2011].
9. Accompanying MATLAB code “solar_pressure.m”; also available in author’s account on the “ecelinsrv” cluster
10. Celestrak. GEO orbital elements. Internet: http://celestrak.com/NORAD/elements/geo.txt [Nov 2011].

Chapter 2: MEO SunSats and the Midnight Power Problem

In the previous chapter we saw that photonic pressure is one nail in the coffin of GEO based SunSats. Although reducing the altitude to 7000 km greatly helps this issue, other daunting challenges remain.

At this altitude, the SunSat is only about 1 Earth radius away. This means that when the ground station is in local night, *especially midnight*, higher-elevation SunSats will be in the Earth's shadow. Only SunSats lower to the horizon will be illuminated by the sun, and able to transmit power. I call this the ***Midnight Power Problem*** (**MPP**). The Following diagram explains:



The sun is shining from the left. The Earth's shadow extends to the right. This view can be either an Earth-equatorial view, in which the SunSat is in a polar orbit; or, it can be an Earth-polar view, where the SunSat is in an equatorial orbit. The SunSat's orbit is orange.

It is due midnight at the ground station. The ground station's ***Effective Midnight Latitude*** (**EML**), is near 0 degrees, or equatorial. EML is geographic latitude corrected for the tilt of the earth and the season. Hence, at winter solstice, a location at 31 degrees N latitude will "effectively" be at 9 degrees, since the earth is tilted 22 degrees away from the sun.

Its ***Acceptance Cone*** is the allowable region above it from which power can come. It is >30 degrees above the horizon, for a total cone width of 120 degrees. Larger cones would create problems on the ground which will be discussed later.

The problem is, at midnight, only a tiny sliver of this cone can possibly have a Sun-lit SunSat in it. The shadow of the Earth creates a Maximum Sunlit Elevation for a given SunSat orbital altitude: the lower the orbit, the lower the Maximum Sunlit Elevation. The accompanying Excel spreadsheet [1] details the calculations for this. Here is a summary table of SunSat altitudes and the corresponding Maximum Sunlit Elevation:

SunSat orbital altitude (km)	***Maximum Sunlit Elevation*** **(degrees above horizon, ground station at midnight)**
5535	30
6975	40
7886	45
8990	50
12181	60

Consider our SunSat orbit of altitude 7000 km, at ground station midnight. A SunSat will be lit by the sun, and sending power down, when it is *no more* than 40 degrees elevation. If our Acceptance Cone *begins* 30 degrees above the horizon, there is only a 10 degree swath from which power may come.

As seen in the diagram, there will be two such 10-degree swaths, at opposite horizons. To ensure continuous power beaming, this orbit must be populated with a constellation of many SunSats. Only this will guarantee that somewhere in that 20 degrees of orbit there is at least one SunSat present. There must be, rather approximately, (360 degrees/circle) / (20 degrees) = 18 SunSats orbiting evenly in this circle to guarantee coverage.

Worse still, that 18-satellite requirement is *just for that one* orbital plane. Multiple orbital planes, similarly populated, would be required to ensure the ground station is always within view of a sun-lit SunSat.

This is a huge amount! This presents a huge penalty: going from one SunSat in GEO orbit to an entire constellation MEO. Unfortunately, the Photonic Pressure Problem forces this.

This table also helps explain why we cannot further reduce the SunSat's orbit much below 7000 km, although this would desirably diminish the effects of photonic pressure. At 5500 km, the Maximum Sunlit Elevation will be only 30 degrees – right at the border of our Acceptance Cone.

The Midnight Power Problem is very relevant and has to be addressed by any realistic SunSat system. Space Solar Power's biggest trump card to play is its promise of 24 hour/day baseload power [2]. Take this away, and SSP is like a house of cards that tumbles to the ground. Terrestrial Power starts to make a better case.

Summary

The Midnight Power Problem imposes a *minimum* SunSat altitude of approximately 7000 km. It also imposes a cost penalty of at least 18 times, and likely multiples of that, what a single GEO SunSat would cost. This cost is likely fatal to any serious efforts to use SunSats for baseload power.

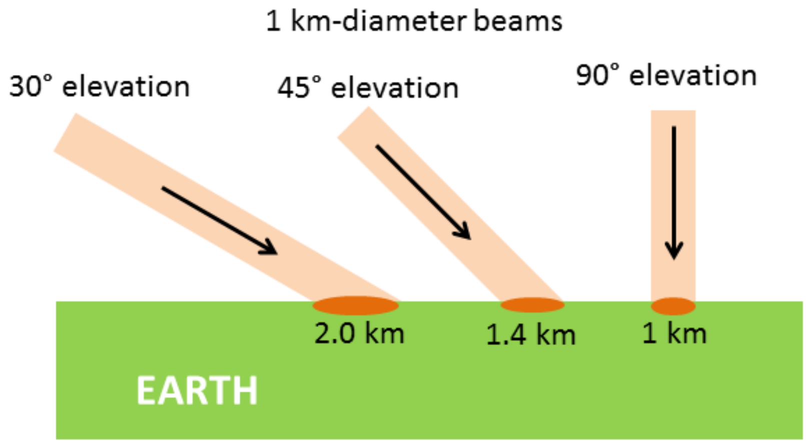
The photonic pressure problem imposes a *maximum* SunSat altitude of about the same. Higher MEO orbits would alleviate the need for larger constellations, by giving a higher Maximum Sunlit Elevation. Unfortunately, as was seen in the previous chapter, even the 7000 km orbit was marginally unstable. 7000 km may not even be achievable, much less higher orbits.

End Notes

1. Accompanying excel spreadsheet "solar1.xlsx", tab "MEO SunSat"
2. Space Solar Power Workshop. (2006, Apr. 7) "Photovoltaics" in *Silent Power*. [On-line]. ch. 6. Available: http://www.sspi.gatech.edu/photovoltaics2006.pdf [Nov 2011].

Chapter 3: Surface Considerations: Land Area

Assume our SunSat transmits a narrow, conical (nearly cylindrical) beam with circular cross-section. The incoming beam will get "stretched" from a circle to an ellipse depending on the angle it strikes the ground. The following diagram illustrates this:



Depending on the particular MEO constellation, the azimuth from which it comes could be anywhere. As a result, depending on the Acceptance Cone of the Ground Station, the actual ground area which must be populated with rectennas will be much larger than the actual beam:

Acceptance Cone minimum elevation (degrees)	**Maximum "stretch" for a 1km-diameter incoming beam (km)**	**Resulting ground area which must be populated with rectennas (km^2)**
20	2.9	6.6
30	2.0	3.14
45	1.41	1.56
90 (reference)	1.0	0.79

In the last chapter, a minimum incoming elevation of 30 degrees was adopted. The above table describes one serious shortcoming of reducing this to 20 degrees or lower. The land area which must be populated with rectennas doubles.

For wider beams from our SunSat, rectenna area and cost really mushroom. This makes a strong case for keeping the beam width as small as practical.

SunSat microwave beam diameter, nominal (km)	Maximum "stretch" on ground, for elevation angle 30 degrees. (km)	Resulting ground area which must be populated with rectennas (km^2)	Estimated Rectenna Cost, (million) US Dollars $	
			At $10/m^2	At $100/m^2
1	2	3.14	31	314
2	4	12.6	126	1.3 billion
For Comparison: Blythe Solar Power Project[1][2], California		**24.1**		
3 (recommended)	**6**	**28.3**	**283**	**2.8 billion**
5	10	78.5	785	7.9 billion
7.5	15	177	1.8 billion	18 billion
10	20	314	3.1 billion	31 billion

So what constitutes a "reasonable" size SunSat ground station?

For comparison, the Blythe Solar Power Project [1][2] in California is listed. Currently under construction, it will be the largest solar farm on Earth. The entire security perimeter, to include the solar collection and support facilities, will contain 5950 acres, or, about 24.1 km^2. A comparably-sized SunSat facility would accommodate a 2-3 km wide (nominal) MEO SunSat beam. Based on this real-world example, we will adopt a 3 km-wide (nominal) SunSat beam.

Site area & cost could be reduced by half, if the SunSat transmitted a 2 km, instead of 3 km beam. As will be seen in a following chapter, though, even a 3 km beam requires an irrationally sized transmitter dish. 2 km would be even worse.

A smaller transmitter dish, and hence wider beam, could be used on the SunSat. Area (and Ground Station cost) grows as diameter squared, though, so costs rise rapidly. A 5 km beam almost triples site cost. A 10 km beam would multiply site costs by 10. In addition, larger beams are precluded by the hazard to LEO satellites. This aspect will be fully investigated in a later chapter.

Narrowing the acceptance cone would reduce the required ground area and cost. Unfortunately, the Midnight Power Problem precludes this.

Summary

The size of a SunSat ground station is bounded by beam width and required incidence angles. The Real-world example of the Blythe installation suggests a maximum nominal beam width of 3 km.

End Notes

1. California Energy Commission. "Blythe Solar Power Project" Internet: http://www.energy.ca.gov/sitingcases/solar_millennium_blythe/index.html, Jun. 17, 2011 [Nov 2011].
2. J. Murray, editor. (2011, Aug. 22). World's Largest Solar Farm Switches from thermal to PV. *BusinessGreen* [On-line]. Available: http://www.businessgreen.com/bg/news/2103170/worlds-largest-solar-farm-switches-thermal-pv [Nov 2011].

Chapter 4: Protecting Aircraft

In the FAQ page of the Space Solar Power Workshop were some particularly questionable comments. With regard to aviation, it states [1, item 12]:

> … airplanes are able to safely cross the path of the beam without any problem because the beam bounces off the aluminum of the plane…

Has the author never put his aluminum-wrapped lunch in a microwave oven?

Besides this, an aircraft is not a solid surface of aluminum. It has windows beyond which are human heads. It also has external antennas, which by design bring electromagnetic energy from the outside to the inside.

What about private aircraft, some of which are simply wood and canvas? Or rotorcraft, or military aircraft, with large glass cockpits?

Consider that on most flights [2][3] any radio receiving or transmitting equipment is disallowed, including a simple FM radio. Computer peripherals are not even allowed, for fear their interface cable will trickle out a few microwatts of RFI.

Does the author really believe that a microwave beam with enough power to run a small city is no big deal to the FAA? When I can't even listen to a FM radio without an Air Marshall wrestling me to the ground?

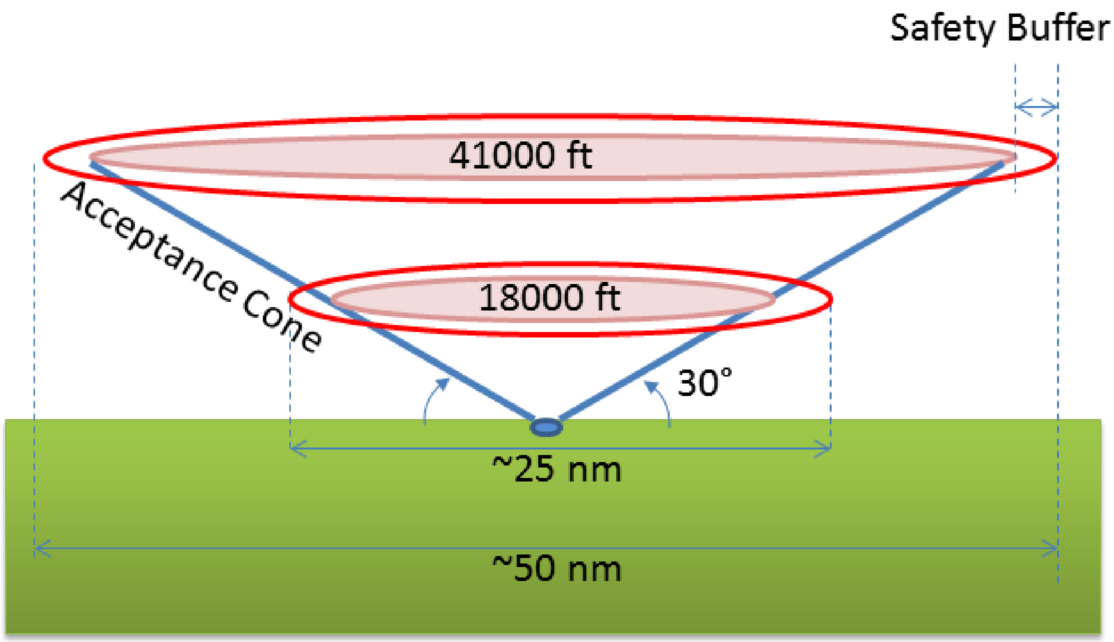
Between the Federal Aviation Administration, the individual airlines, and the individual pilots who are flying the aircraft, there is no way a passenger aircraft is ever going to fly into this beam. The liability is too great. When human life is involved (not to mention a million-dollar aircraft), there is always an abundance of caution.

That being said, the US Airspace System has a number of structures which prohibit the nearby placement of a SunSat system [4][5]:

1. Airports
2. Military Operations Areas [4, ch. 3_4_5] [5, p. 4]
3. Restricted Areas [4, ch. 3_4_3] [5, p. 2]
4. Prohibited Areas [4, ch. 3_4_2] [5, p. 2]

5. Victor Airways [4, ch. 5_3_4] [5, pp. 4-5,7]
6. Jet Routes [4, ch. 5_3_4] [5, pp. 5-7]
7. Military Training Routes [4, ch. 3_5_2] [5, p. 4]

In the last chapter, the “footprint” of a SunSat beam was examined on the surface. What about the “footprint” of a beam in the skies above?



This diagram depicts a SunSat ground station, with an acceptance cone of >30 degrees elevation. The edges of the cone are drawn up to an altitude of 41000 ft. An intermediate altitude of 18000 feet is drawn as well.

A survey of common Jet aircraft (Airbus 320[6], Boeing 737[7], Boeing 777[8], and Gulfstream IV [9]) was conducted. They have service ceilings of 39000-45000 feet, and cruising speeds of 444-490 knots. For the purposes of this chapter we will consider a cruise altitude of 41000 feet, and a speed of 450 knots.

The area within the acceptance cone is subject to high power microwave radiation. This area, coupled with a safety buffer, constitutes a high-altitude no-fly zone which exists around the ground station. An excel spreadsheet [10] was written to assist in this calculation. A buffer of 2-minutes flight time at cruise speed (approx. 15 nautical miles) was adopted. A pilot who accidentally strays in would have two minutes time to notice (or be told by ATC) about the error, initiate steps to turn around, and be pointed away from the acceptance cone before he actually enters it.

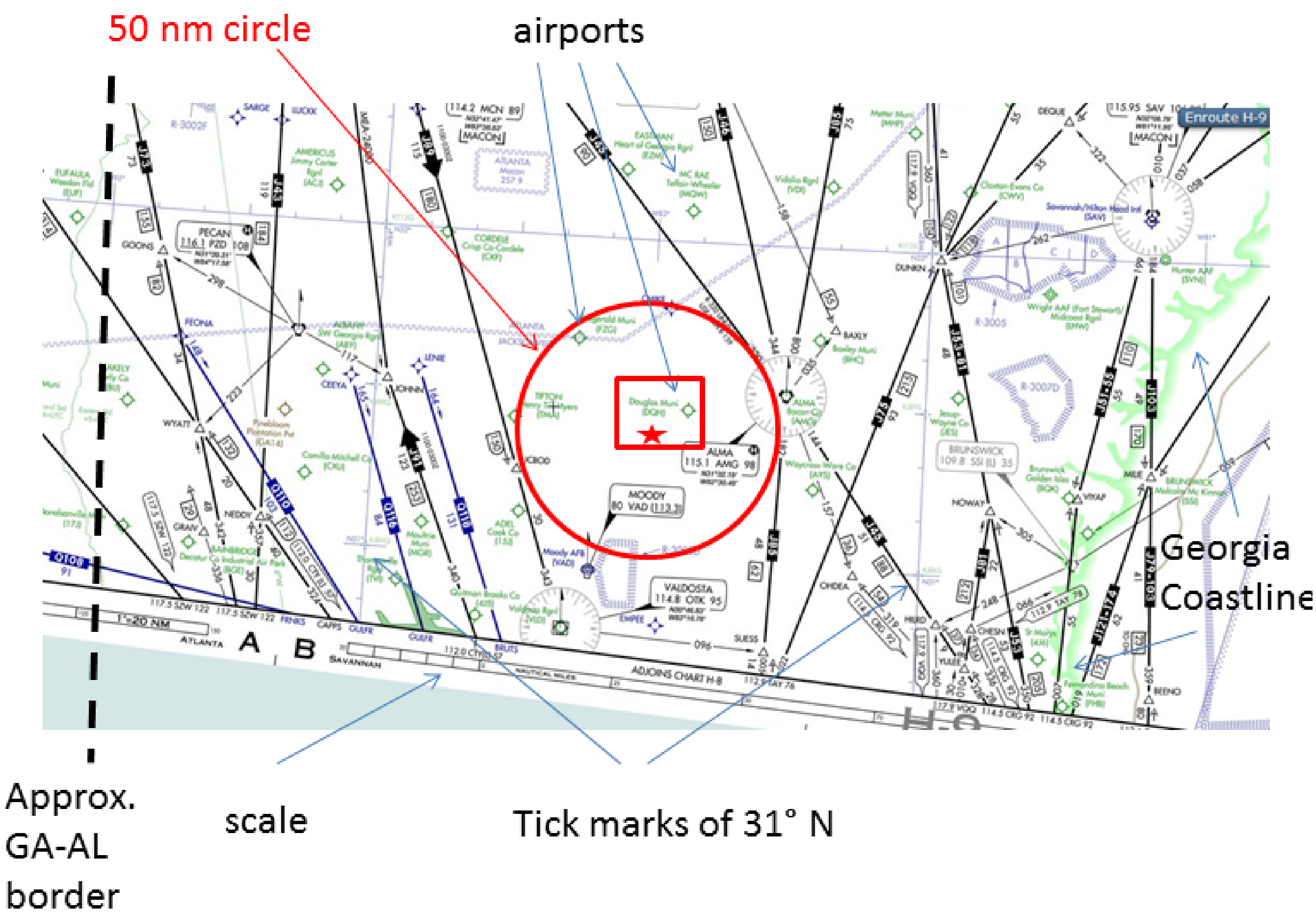
The result is an approximately 50 nautical mile diameter no-fly zone at 41000 feet. As will be seen, this is difficult, if not impossible, to fit within the existing US airspace infrastructure.

The US Airspace has “highways” in it. Above 18000 feet MSL are “Jetways” in “Class A” airspace. These Jetways are depicted on FAA charts called “High Altitude Enroute Charts”. [4, ch. 5_3_4, 9_1_4_b; pp. PCG A-3, PCG J-1] [5, pp. 1-11]

Below 18000 feet are “Victor Airways”, for civilian use, and “Military Training Routes”. In addition to these linear routes, there are entire volumes of sky categorized as “Military Operations Areas”, “Prohibited Airspace”, “Restricted Airspace”, “Alert Areas”, and yet other designations. These structures are depicted on FAA charts called “Low Altitude Enroute Charts”. [5, pp. 1-11]

The no-fly zone was also calculated for a height of 18000 feet, to see how the ground station would fit. With a 2-minute buffer at a reduced cruise speed of 250 knots, an approximate 25 nautical mile diameter no-fly zone was calculated.

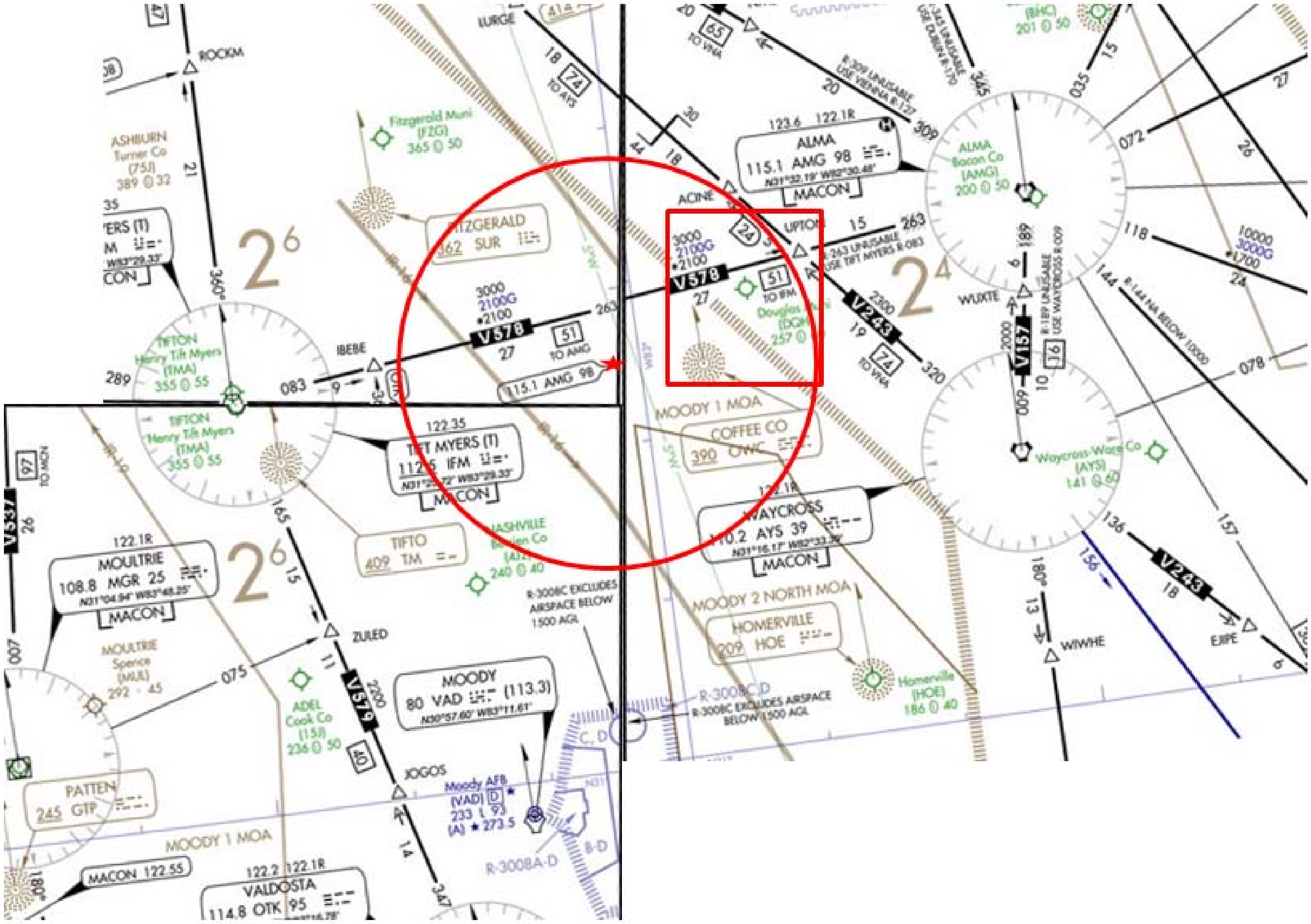
This existing infrastructure is complex, and an examination of current charts shows little, if any, room.



Above is the “High Altitude” chart for South Georgia. It is chart “H-9” and is available from skyvector.com [11]. Noted are the tick marks for 31° N, the Georgia Coast, and the Alabama border. The black lines with “J” tags are Jet Routes. The green circles with names nearby are airports. [5, pp. 1-11]

At the bottom of the chart is the scale, in nautical miles. The circle drawn is a 50 nm diameter circle. The center of which is noted with a star. A nearby airport is highlighted in a red square.

As can be seen, the existing Jet Route infrastructure leaves little or no room to put a 50-nm wide zone anywhere in South Georgia. Indeed only the one location depicted is even possible. Turning to the Low Altitude chart [11], we see even this location is not eligible.

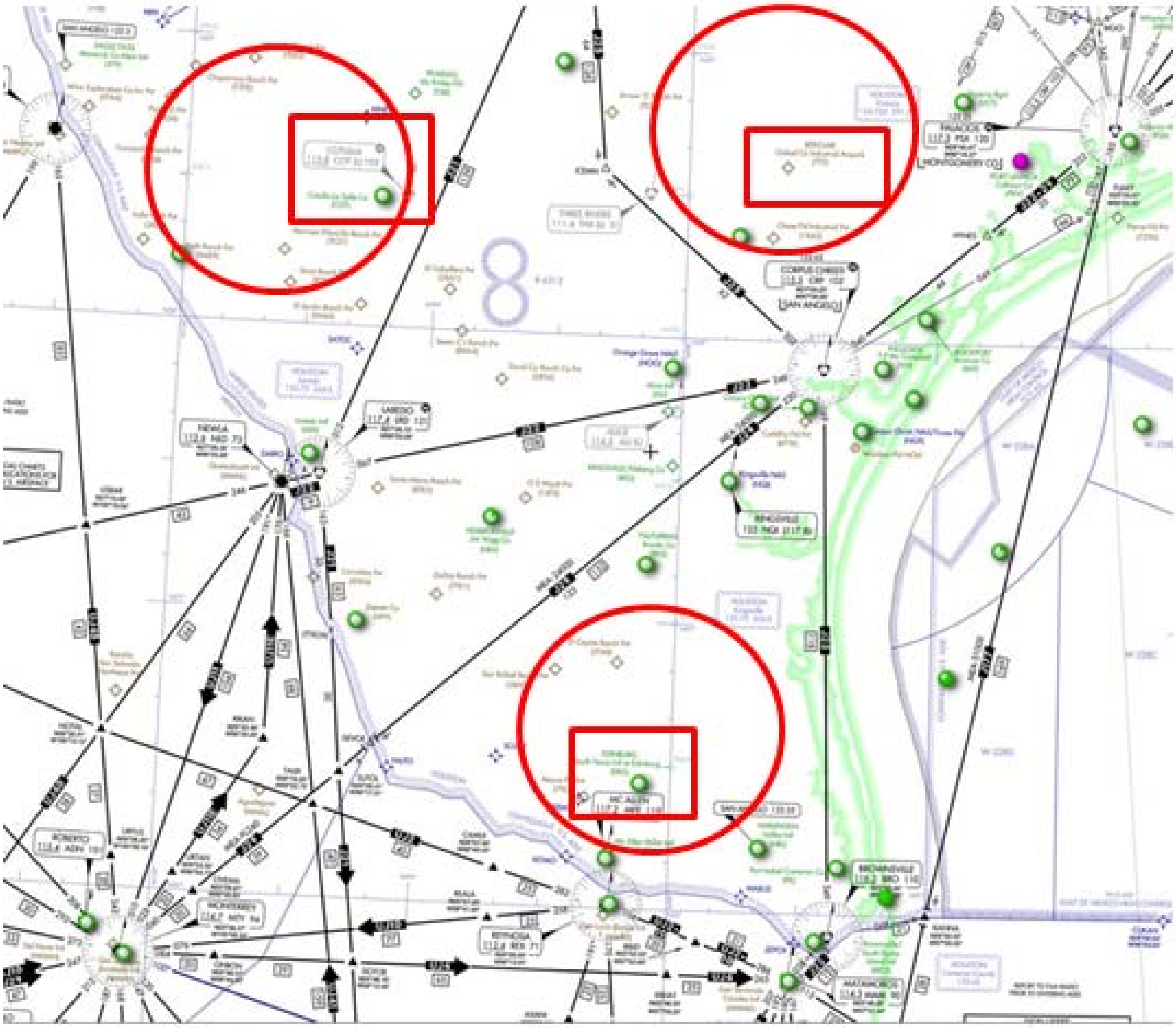


The area in question straddles three FAA charts (L18, L22, L24), hence the three separate blocks combined. The location is the exact same, though, denoted by the red star. The same airport, Douglas Municipal, is in a red square. This diameter is the reduced 25 nm of the 18000 ft no-fly zone.

As can be clearly seen, the Victor Airway V578 runs right through it. There is also a military route, “IR 16”. Since this was the only candidate location, the conclusion is no ground station can be put in South Georgia.

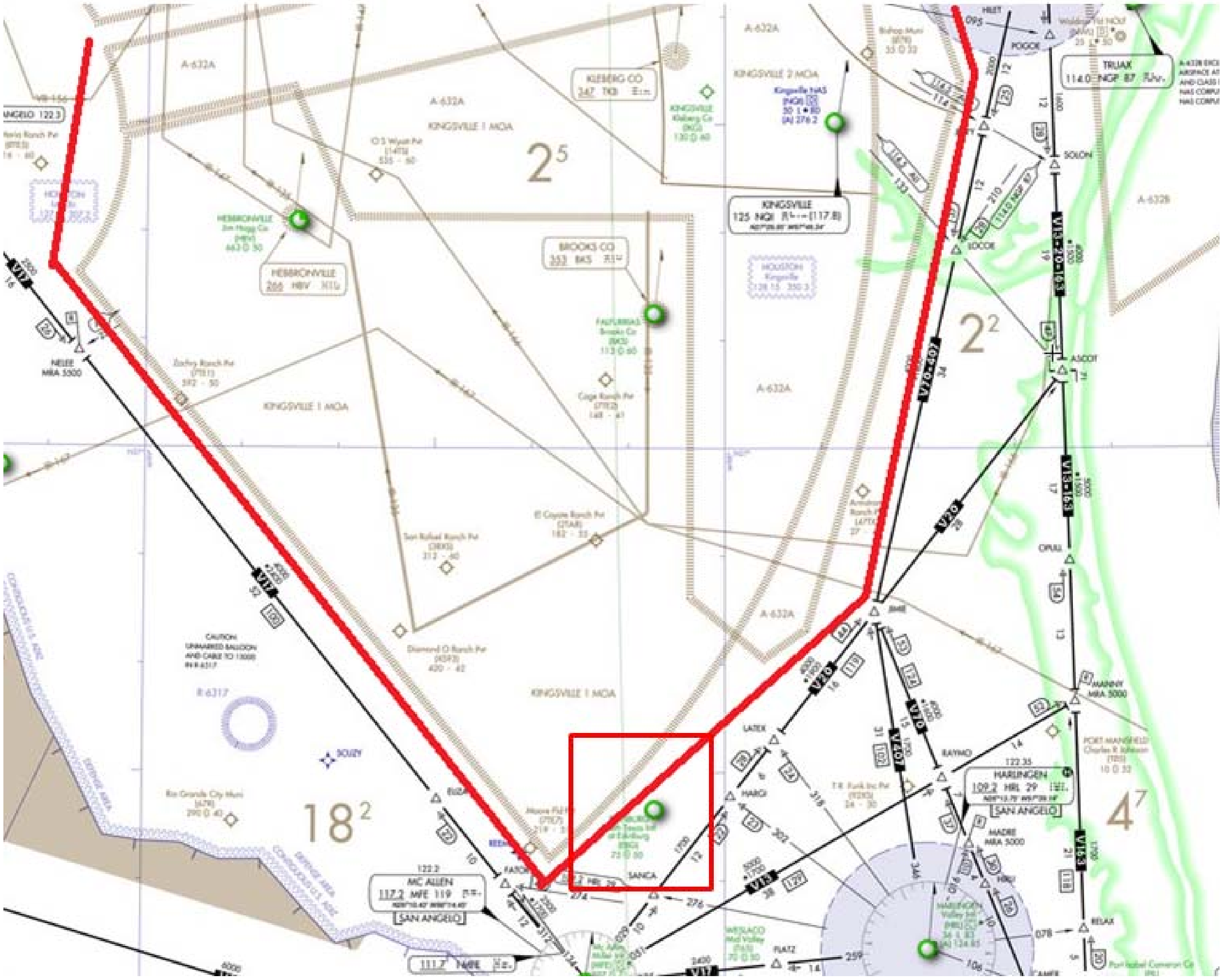
A similar situation existed for the proposed South Texas SunSat Ground Station. The following is Chart “H-7” [11] depicting South Texas. The Gulf of Mexico and the Mexican Border are both prominent.

As can be seen, the high-altitude chart narrows down the possibilities to three candidate regions. Note the figure-8 shaped restricted area in the middle region which prohibits placing one here.



Examination of the low-altitude charts for these three regions eliminates all three as possibilities. There are extensive Military Operations Areas in South Texas.

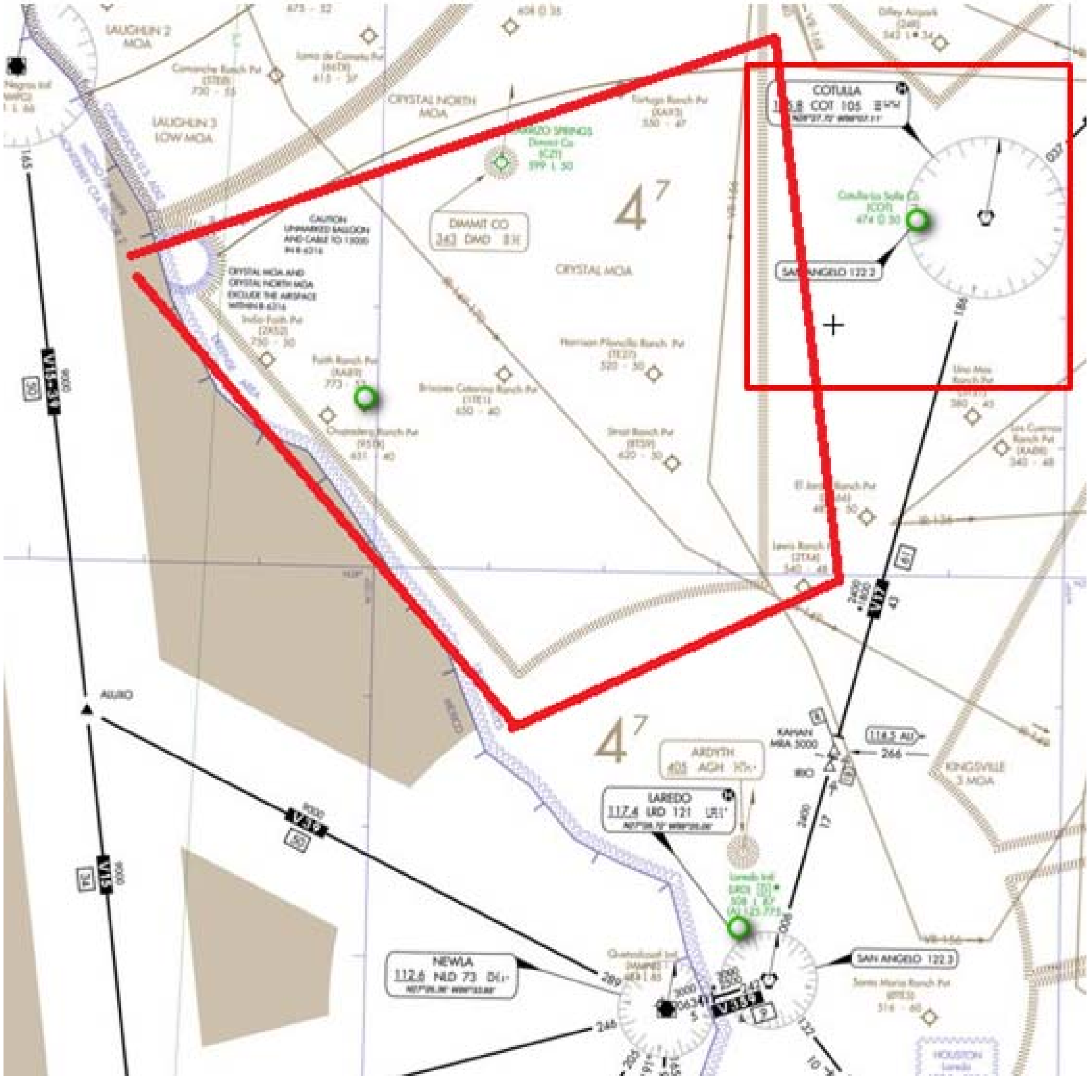
To help identify these regions in the low-altitude charts, Edinburg Airport in the South, Berclair Airport in the Northeast, and Cotulla VOR in the Northwest have been boxed.



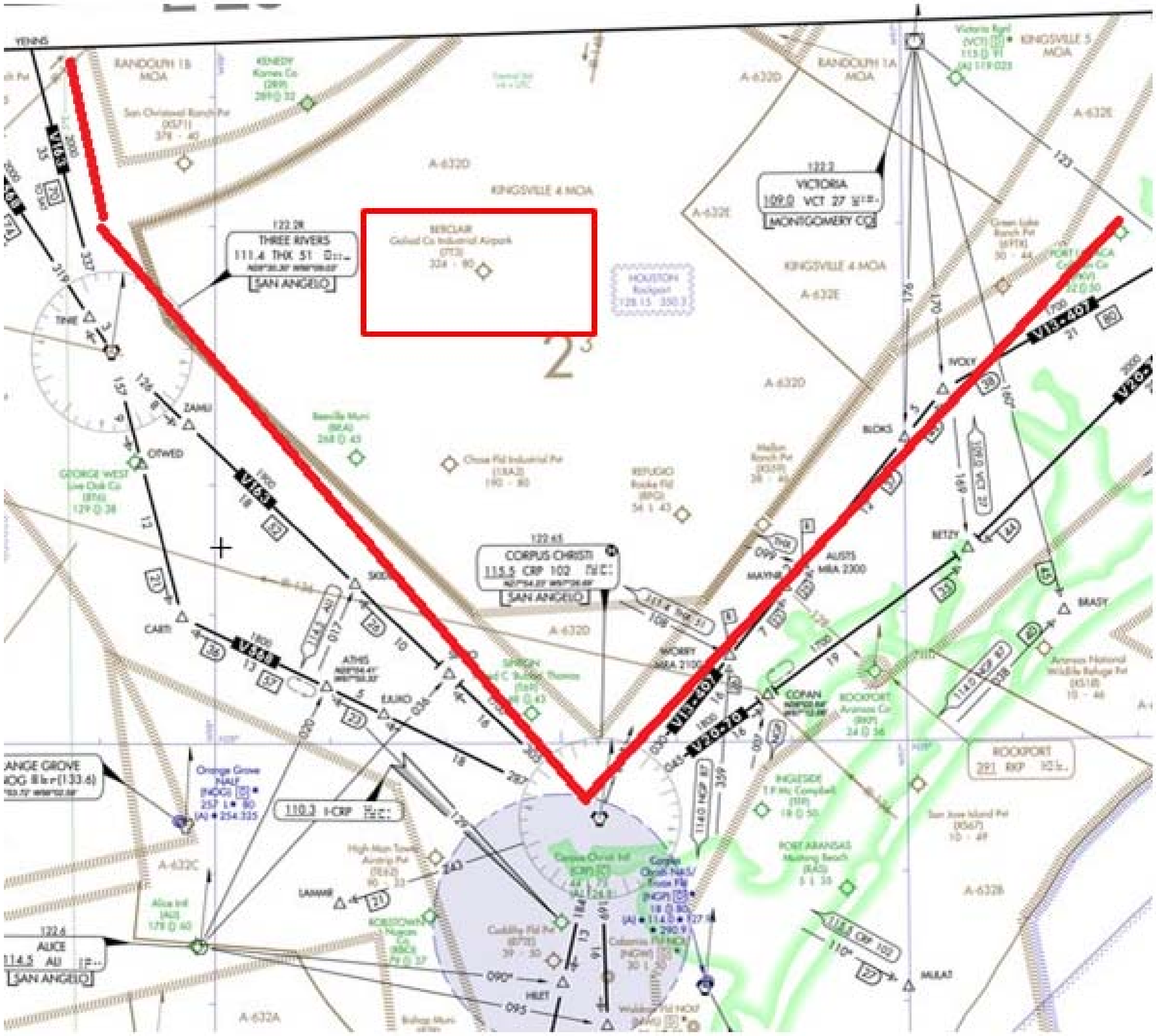
This is from chart "L-20" [11], showing the Southern candidate zone. The box is Edinburg Airport, also boxed in the high-altitude chart.

This area has Victor Airways to the East and South. In addition, humongous Military Operations Areas and Military Routes (depicted in brown on the chart) carpet the southern part of Texas. The large depicted red area highlights them: in particular, "KINGSVILLE 1 MOA".

This Southern zone cannot be considered for a Ground Station.



This is also from chart “L-20”. Cotulla VOR is boxed. The candidate location was west of here. Unfortunately, “CRYSTAL MOA”, highlighted in red, precludes putting anything there. Strike two.



And finally, strike three. This is the chart, also "L-20" [11] of the Northeast candidate location, centered over Berclair airport. Again, this is right in the middle of Military Operations Areas, particularly, "KINGSVILLE 4 MOA".

Summary

A thorough analysis of airspace over two of the 8 requested locations shows no available airspace to squeeze in the massive no-fly zones required for a Ground Station. Perhaps narrower Acceptance Cones could be fit someplace, but with unacceptable consequences: sporadic delivery of nighttime power, and surrendering the promise of baseload power. In any case, no matter how narrow the acceptance cone, a safety buffer would be required. For a 2-minute buffer at cruise speed, this adds at least 30 nm to *any* diameter at 41000 feet.

The threat of a SunSat microwave beam to aircraft cannot be rationalized away. For one thing, the aircraft doesn't belong to you! Second, matters of human safety are always considered with an abundance of caution.

End Notes

1. Space Solar Power Institute. "Frequently Asked Questions." Internet: http://solarsat.org/faq.htm [Nov 2011].
2. Delta Air Lines. "Delta In-flight Information about Portable Electronic Devices." Internet: http://www.delta.com/traveling_checkin/inflight_services/connectivity/personal_electronic_devices/index.jsp#cannot [Nov 2011].
3. United Air Lines. "Baggage restrictions; Electronic device policy." Internet: http://www.united.com/page/article/0,6722,1036,00.html [Nov 2011].
4. Federal Aviation Administration. (2010, Feb 11). *Aeronautical Information Manual*. [On-line]. Available: http://www.faa.gov/air_traffic/publications/ATPubs/AIM/aim.pdf [Nov 2011]
5. Federal Aviation Administration. (2008). "The National Airspace System," in *Instrument Flying handbook*. [On-line]. ch. 8. Available: http://www.faa.gov/library/manuals/aviation/instrument_flying_handbook/media/FAA-H-8083-15A%20-%20Chapter%2008.pdf [Nov 2011]
6. Wikipedia. "Airbus 320." Internet: http://en.wikipedia.org/wiki/A320 [Nov 2011]
7. Wikipedia. "Boeing 737." Internet: http://en.wikipedia.org/wiki/Boeing_737 [Nov 2011]
8. Wikipedia. "Boeing 777." Internet: http://en.wikipedia.org/wiki/Boeing_777 [Nov 2011]
9. Wikipedia. "Gulfstream IV." Internet: http://en.wikipedia.org/wiki/Gulfstream_IV [Nov 2011]
10. Accompanying EXCEL SPREADSHEET "solar 1.xlsx", tab "no fly zone"
11. Aeronautical charts from http://skyvector.com [Nov 2011]. Hover mouse over the "Charts" globe icon; then select "Enroute Low" or "Enroute High"

Chapter 5: Protecting People

Human beings must be protected from the radiation the SunSat beams to the surface. What are the limits and guidelines for human exposure? The Federal Communications Commission, Office of Engineering and Technology [1], has published a document called bulletin 56 [2]. In it, on page 15, is a table summarizing RF exposure limits for various frequencies. The table is also published in the US Code of Federal Regulations, 47 CFR 1.1310 [3]. The data is provided in units of mW/cm^2. For more convenient analysis it is converted here to W/m^2. With regard to microwave and millimeter wave radiation, the statutory limits are:

Notes	**mW/cm^2**	**W/m^2**
FCC OET bulletin 56: General Population, Maximum Permissible Exposure 1.5-100 GHz	1	10
FCC OET bulletin 56: Occupational/Controlled, Maximum Permissible Exposure 1.5-100 GHz	5	50
For reference:		
5 Gigawatt beam, spread over 3km/6km diameter, average density		708 / 177
10 Gigawatt beam, spread over 3km/6km diameter, average density		1415 / 354

These two limits are not peculiar to the USA. They have been adopted by the UK [4], Canada [5], and Australia [6] as well.

For reference, sample (average) power densities are provided for 5 GW and 10 GW beams, spread over a 3km or 6km diameter circle. The results are stark.

The Ground Station far exceeds exposure guidelines, both for the general public and for workers. The SSPI statement [7, item 3] that it “effectively uses no land,” and “could have green farms underneath” is bizarre. Any number of factors could allow radiation leakage to the ground: discontinuity between adjacent rectenna panels, or damage from wind, hail, or other meteorology, routine wear-and-tear, vandalism or sabotage. When human life is involved, an abundance of caution is always used. Rectenna sites will be uninhabited and tightly controlled, with strict security perimeters. There will not be farm workers or curious onlookers milling about. The lawyers will make certain of that.

When Ground Station employees are on the ground, the beam will most certainly have to be turned off. This further erodes the promise of Space Solar Power as 24/7 baseload energy.

For areas outside of the security perimeter, exposure limits for the general public must be followed. The sidelobe levels of the transmitter must be low enough so that power densities are below the 10 W/m^2 limit. This challenge will be addressed in the next chapter.

Consider the overall risk of this endeavor. You have a SunSat zooming around the Earth at 12000 miles per hour. It is aiming an extremely narrow beam at a pinpoint on the ground 7000 km away – that's about twice the distance from New York to Los Angeles. All the while, it is continuously adjusting the dish angle to maintain that pinpoint aim.

How can anybody guarantee this will never go wrong? That is ridiculous!

Something can – and will – go wrong at some point: perhaps a mechanical failure, electrical problem, software error, or simply a component which reached its natural end of life. What if a populated area got bathed in hundreds of watts per square meter? The lawyers would have a field day with this.

Consider this: the small trickle of RF put out by cell phones was enough to spawn a cottage industry of lawyers suing for cancer. What do you think will happen the first time an elementary school gets barbecued with hundreds or thousands of watts?

Is the risk *really* worth it?

Summary

Space Solar Power presents a severe risk to humans on the ground. Power densities at the Ground Station are about 10-100 times the legal limit for the General Public. These limits are multinational and are shared by the US, Canada, Australia, and the UK. The legal liability risks here are severe.

As for occupational exposure to Ground Station employees, power densities again exceed multinational standards by a factor of about 3-30. Any inspection or maintenance by personnel on the ground will require the beam to be turned off. This undermines the promise of SSP as 24/7 baseload power.

End Notes

1. Federal Communications Commission, Office of Engineering and Technology. “Radio Frequency Safety.” Internet: http://transition.fcc.gov/oet/rfsafety/, Apr. 20, 2011 [Nov 2011].
2. R. Cleveland, J. Ulcek. “Questions and Answers about Biological Effects and Potential Hazards of Radiofrequency Electromagnetic Fields,” Federal Communications Commission, Office of Engineering and Technology, Wash., DC., Bulletin 56, 4th Ed, Aug. 1999. Available: http://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet56/oet56e4.pdf [Nov 2011]
3. US Code: 47 CFR 1.1310. Available: http://edocket.access.gpo.gov/cfr_2004/octqtr/47cfr1.1310.htm [Nov 2011].
4. F. McKinlay et al. “Advice on Limiting Exposure to Electromagnetic Fields,” National Radiological Protection Board, Oxfordshire, UK., Vol. 15 No. 2, 2004. Available: http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1194947415497 [Nov 2011].
5. Health Canada. “Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz,” Consumer and Clinical Radiation Protection Bureau, Ottawa, Canada, Safety Code 6, 2009. Available in accompanying documentation, and by request via: http://www.hc-sc.gc.ca/ewh-semt/pubs/radiation/radio_guide-lignes_direct-eng.php [Nov 2011]
6. Australian Radiation Protection and Nuclear Safety Agency. “Maximum Exposure Levels to Radiofrequency Fields 3 kHz to 300 GHz,” ARPNSA, Canberra, Australia, May 8, 2003. Available: http://www.arpansa.gov.au/publications/codes/rps3.cfm [Nov 2011]
7. Space Solar Power Institute. “Frequently Asked Questions.” Internet: http://solarsat.org/faq.htm [Nov 2011].

Chapter 6: Are SunSat Transmitter Dishes even practical?

A SunSat must focus a microwave beam onto just a few kilometers of ground, while thousands of kilometers away. This demands a large dish with a narrow beamwidth. Furthermore, sidelobe suppression is required here. Areas outside the Ground Station must receive power below the exposure limit of 10 W/m^2. Large dishes carry with them impracticalities for how you get them to space, or, assemble them in space.

At the same time, smaller dishes present their own issues. This dish is transmitting gigawatts of power. The power densities at the dish surface can get ridiculous. Are ohmic losses going to heat the dish, possibly unevenly, and make it warp? Unsatisfactory sidelobes will result. Is there going to be arcing from the currents induced on the dish surface, like a piece of foil in a microwave oven?

Finally, MEO dishes require steering, on the order of 1-2 beamwidths per second. If the steering mechanism fails, who all is going to get hurt by this?

For this investigation, the MATLAB code from homework assignment #2 was employed [1]. Many simulations were run to determine what dish sizes and taper coefficients were necessary. The EXCEL spreadsheet [2] contains these results. The simulation, and the spreadsheet, record dish sizes as “radius.” That data is doubled to “diameter” for the body of this report.

Dish diameters had to be wide enough to narrow the beam down. Taper coefficients had to be sufficient so the first sidelobe was within limit. In addition to the integer taper coefficients used in class, “half” increments were considered as well: 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. In addition, transmit power must be considered. The greater the power, the more sidelobe suppression is required.

For these analyses, null-null beamwidth was considered, instead of 3 dB beamwidth. After all, the point is to harvest energy, not waste it. Wasting half a 10 GW beam is losing 5 GW. From a safety standpoint, that 5 GW might be dangerously spilling over into an uncontrolled area. This safety risk is heightened if there is significant pointing error. Capturing the totality of the main lobe is both a practical and safety imperative.

First, GEO will be considered. At a GEO altitude of 35786 km, beamwidths of one-thousandth to one-hundredth of a degree are required. Simulations revealed dish sizes for 3km wide and 5km wide beams, with legal sidelobe levels. Power density figures are based on a nominal transmit power of 10 GW.

Beam Width on Earth (km)	Beam Width null-null (deg)	Dish Diameter (lambda)	Taper (unitless)	Peak Gain (dBi)	Sidelobe level (dB from peak)	Power density (Earth) at peak, W/m^2	Power density (Earth) from 1st sidelobe, W/m^2
3	0.00481	**46000**	1.5	101.0	-30.1	7822	7.64
5	0.00802	**24000**	1	96.1	-26.1	2531	6.2

These dish sizes are huge!

Consider what this equates to in real terms:

	5.8 GHz	**22 GHz**	**44 GHz**	**90 GHz**	**140 GHz**	**220 GHz**
Surface Tolerance (lambda/8)	6.5 mm	1.7 mm	0.85 mm	0.42 mm	0.27 mm	0.17 mm
Dish Diameter (lambda)	**Dish Diameter (meters)**					
24000 (5km beam)	1241 m	327 m	164 m	80 m	51 m	33 m
46000 (3km beam)	2379 m	627 m	314 m	153 m	99 m	63 m

The project statement said that the ISM bands (i.e. 5.8 GHz) were “preferable” [3]. The data strongly differs. Even for a “relaxed” beam width of 5 km, a dish nearly 12 football fields wide would be necessary, with a surface tolerance of about a quarter of an inch!!

The window around 90 GHz [4] only takes us down to 80 meters (nearly 1 football field) wide, with surface tolerances demanding half a millimeter now (a blade of grass on that field). The next window at 140 GHz isn’t much better, a width of 51 meters (88 feet), with a surface tolerance of only about 3 sheets of paper. As a rule of thumb a sheet of paper is about a tenth of a millimeter thick.

The last practical window at 220 GHz, size is down to 33 meters (109 feet) wide: slightly longer than a basketball court. Unfortunately, surface tolerance is down to 0.17 mm, less than two sheets of paper thick.

There are two possibilities here. Perhaps a very clever way to fold up a really large, lightweight, thin, flimsy dish into a rocket is found. Unfortunately, because it is lightweight, thin, and flimsy, the chances of you making these surface requirements are nonexistent.

Second, this could be assembled in pieces in space. The problem is, you can't bolt together a dish in a dozen or a hundred pieces, and expect it to have nearly the mechanical tolerance as if it were solid. There is always going to be some small degree of wobble and flex to it, and that will distort your parabola, creating dangerous sidelobes. Also, the electrical bonding between panels is paramount. Ohmic losses, or worse, nonlinearities (a crude diode from a poor bond or surface contamination between panels) will be fatal.

Smaller dishes could be adopted if larger beams were acceptable, but they're not. In the following chapter, the threat to LEO satellites will be examined, which can't handle larger beams. Plus, ground costs skyrocket the larger the beam becomes.

<u>This all leads to the conclusion that GEO-based SSP requires thoroughly unrealistic transmitter dishes. Combined with the photon pressure problem, this one-two punch renders this technology impractical.</u>

What about MEO?

Let us consider the MEO SunSat at an altitude of about 7000 km. This altitude represents merely the shortest possible distance from the SunSat to the ground. The EXCEL spreadsheet [5] shows us the slant distance for this SunSat can get as high as 8300 km when it is only 40 degrees above the horizon. For the sake of this analysis, a distance of 8300 km will be used for antenna size calculations. The simulations were rerun [6], and dish sizes went down by a factor of 4.3:

Beam Width on Ground (km)	Beam Width null-null (deg)	Dish Diameter (lambda)	Taper (unitless)	Peak Gain (dBi)	Sidelobe level (dB from peak)	Power density (Earth) at peak, W/m^2	Power density (Earth) from 1st sidelobe, W/m^2
3	0.02076	10700	1.5	88.3	-30.1	7810	7.63
5	0.0347	5600	1	83.5	-26.1	2586	6.35

	5.8 GHz	22 GHz	44 GHz	90 GHz	140 GHz	220 GHz
Surface Tolerance (lambda/8)	6.5 mm	1.7 mm	0.85 mm	0.42 mm	0.27 mm	0.17 mm
Dish Diameter (lambda)	**Dish Diameter (meters)**					
5600 (5km beam)	290 m	76 m	38 m	19 m	12 m	8 m
10700 (3km beam)	533 m	146 m	73 m	36 m	23 m	15 m

For the MEO SunSat, 5.8 GHz is still unrealistic, even for a relaxed 5 km wide beam. The dish diameter would be about three football fields wide – and this monstrosity would have to be steered.

Even the relaxed 5km wide beam demands 19m (63 feet) at 90 GHz, 12m (40 feet) at 140 GHz, and 8m (26 feet) at 220 GHz. It's still an open question whether this dish can be assembled piece-wise, while maintaining the strict (< 0.5 mm) surface tolerances required.

The Steering Problem

Going to MEO merely trades one problem for another. This ~20m dish must now be steered. Pinpoint aim must be maintained while soaring above the earth at over 10000 MPH.

Is this realistic?

Orbital velocity at 7000 km altitude is about 5.5 km/s. The Ground Station, when directly beneath the SunSat, will be changing direction at approximately (5.5 / 7000) rad/sec, or 0.045

deg/sec. Consider from the table above, the beamwidth of the 3km beam is 0.021 degrees, and the 5km beam is 0.035 degrees.

The dish must be pointed within a *hundredth* of one degree accuracy. Even then, every second, the SunSat must precisely steer this dish 1-2 whole beam widths - with no mistakes. Or else somebody gets hurt on the ground.

The Dish Power Density Issue

Then power density creeps in as an issue. Consider a dish 20 m in diameter. For a 10 GW beam, the average power density over the dish surface will be 32 megawatts per square meter. What metal is going to stand up to this? The dish will probably just start melting. And what about a larger dish then? Even a 100m diameter dish (1 football field wide) would have an average power density of 1.3 megawatts per square meter: same problem.

And even if it doesn't melt, consider that the power density, and hence heating and expansion, is uneven. We are using a tapered illumination function. Power density will be greatest towards the center, and less and less outward. The center area will heat up quicker and expand more. What happens when a metallic body heats unevenly? It warps and bends. The required surface tolerances will get thrown out the window and sidelobes will go everywhere.

Also consider in space, there is no easy way to dissipate heat, only through radiating it [4].

The Rain Issue

But even if all these issues are overcome, there is a critical flaw with millimeter wave SSP. Dr. Komerath [4, notes p. 11] candidly admits:

> But how good is 220 (or 140) GHz in other aspects? The news is bad. Both are terrible when there is rain in the air. Only the regime below 10 GHz appears to offer promise for transmission through rain. But this is a false promise, in my opinion.

This is a sobering requiem for MMW SSP. His figure 7.3 [4, notes p. 13] shows light-moderate rain (or fog) attenuation for millimeter wave in the 1-3 dB/km range. Below 10 GHz this plummets to 0.01-0.1 dB/km. Bear in mind, SSP's greatest trump card is 24/7 baseload power. Selective availability due to rain undermines this, and puts terrestrial power on a more even playing field.

Summary

Excessive dish sizes render GEO based SSP impractical. MEO merely trades one problem for another: achievable dish sizes which must be precisely steered 1-2 beamwidths per second, or else power is interrupted and people get hurt.

To obtain these dish sizes, millimeter wave must be used, which suffers severely from rain or fog at the Ground Station, undermining availability of baseload power. Also, the surface tolerances of millimeter wave dishes are well under 1 mm.

Regardless of wavelength or altitude, power densities at the dish surface are on the order of megawatts per square meter. If the dish doesn't melt outright, it will certainly warp from tapered illumination, and hence, uneven heating and expansion.

End Notes

1. Accompanying MATLAB code, " tapered_illumination.m"; also available on the Author's "ecelinsrv" account.
2. Accompanying EXCEL spreadsheet, "solar 2.xlsx", tab "dish simulations GEO SunSats"
3. G. Durgin. (2011, Sep.) *Satellite Communications Class Project: Space Solar Power* [Online]. Available: http://www.propagation.gatech.edu/ECE6390/project/Fall2011/SatCom_Project_2011.pdf [Nov 2011]
4. N. Komerath. ECE6390. Class lecture, Topic: "The Space Power Grid Approach to Space Solar Power." Georgia Institute of Technology, Atlanta, GA, Sep. 9, 2011. Available: http://streaming1.ece.gatech.edu/research/labs/propagation/ECE6390/notes/video/Lecture110908/ece_6390_20110908.wmv, [Nov 2011]. Notes available: http://www.propagation.gatech.edu/ECE6390/notes/SSP_SPGlecture20110908.pdf [Nov 2011].
5. Accompanying EXCEL spreadsheet, "solar 1.xlsx", tab "MEO SunSat"
6. Accompanying EXCEL spreadsheet, "solar 2.xlsx", tab "dish simulations MEO SunSats"

Chapter 7: The Threat of SSP to LEO Earth Satellites

SSP presents a very real threat to Satellites in Earth orbit. These beams of gigawatt-level intensity have the potential to damage or destroy a satellite which transits through the beam. These "innocent" satellites belong to a diverse ownership of nations and corporations. Anybody who deploys a SunSat system has no right to play Russian roulette with expensive property that does not belong to them.

Therefore, out of an abundance of caution, any exposure must be avoided. Absurd rationalizations about the duration or intensity of exposure fall on deaf ears when you are dealing with somebody else's multimillion dollar satellites.

The following analysis will help quantify the substantial probabilities of beam-satellite encounters. It considers 8 geostationary SunSats each sending a beam to its own ground station. The threat to the LEO satellite population is quantified. First it is estimated using some common-sense assumptions, then, fine-tuned in a C code simulation.

The clear conclusion is that any SunSat system actually deployed must have a comprehensive computer simulation system on the ground. This system will predict when beam intercepts will occur, and cycle the beam off accordingly. This is yet another reason why SSP cannot promise 24/7 baseload power.

The satellite population of Earth's Orbit

The "Union of Concerned Scientists" maintains a database of all active satellites in earth orbit [1]. Their latest data set is current as of 8/31/2011. By their count, there are 974 *operating* satellites in earth orbit. They break this down to LEO: 466, MEO: 63, Elliptical: 36, and GEO: 409. This figure does not include nonfunctioning or abandoned satellites, or, discarded rocket stages or other "space trash".

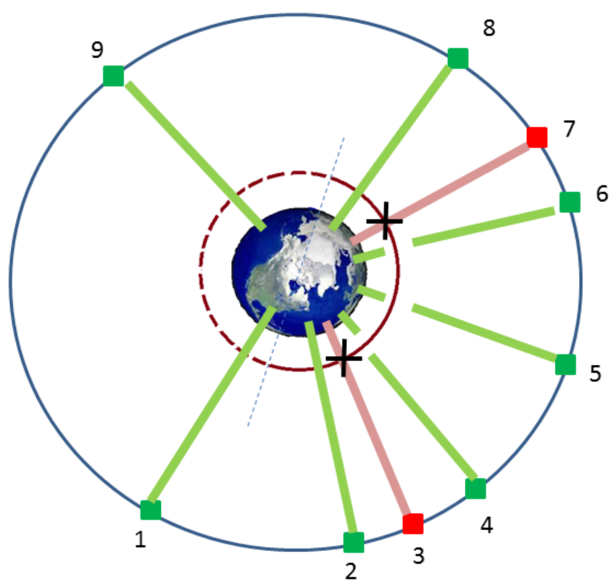
For the purposes of this analysis, we will examine a SSP satellite in GEO orbit beaming down to one of our eight ground stations. Presumably, other "innocent" GEO satellites, at approximately our same altitude, should be safe. Satellites at LEO will not be so fortunate.

SunSat in GEO orbit (right) with two possible groundstation beams.

This above diagram depicts the Earth, a SunSat in GEO orbit, and the side-on view of a LEO orbit (solid dark red). The dashed lines represent two possible beams. The upper, green, beam is going to a ground station at higher latitude, say, 45 degrees. The lower, red, beam is going to a ground station near the equator. As the SunSat makes a complete orbit around the earth in a sidereal day, we can see that the red beam would intersect the orbital track at two points, once in its ascending half, and again in its descending half. The orbit, however, “fits” completely underneath the green beam, so it presents no threat to this satellite.

If the LEO had a larger altitude or inclination, then more or all SunSat beams would pose a risk.

Let’s take a polar view of what this LEO-beam encounter would look like:



Polar view of a GEO SSP beam intersecting a LEO orbit

This is a view from above the North Pole. The brown circle represents a LEO orbit. The dashed blue line separates where its orbit dips above or below the equator; the dashed brown line denotes the orbit south of the equator, the solid brown line denotes the orbit north of the equator. This diagram only depicts the orbital track of the LEO, not its specific location.

The outer orbit is a SSP SunSat in GEO orbit. It is beaming towards a northern hemisphere ground station. We indicate, using numerals 1-9, various points as the SunSat progresses in its counterclockwise orbit. The thick, solid green or red lines denote the beam being sent to the ground station. Depending on the location of the SunSat, this beam will either be below, above, or intersecting the LEO's orbital track.

1. The beam is coming in "above" the LEO orbit. The LEO orbit is still well "below" it, in the southern hemisphere.
2. The distance between its beam and the LEO orbit is closing in. The LEO orbit is now into the northern hemisphere and closing rapidly.
3. The SunSat's gigawatt microwave beam sweeps across the LEO's orbit. Hopefully the satellite wasn't there when it happened!!
4. The SunSat's beam is now "below" the LEO's orbit. The diagram emphasizes this by "dashing" the beam.
5. The SunSat's beam is now well below the LEO orbit, which is now at its highest latitude.
6. The LEO orbit is again dipping towards the southern hemisphere, and its distance to the beam is dropping.
7. The beam again sweeps across the LEO orbital track. Hopefully the LEO wasn't there!
8. The beam is now well above the LEO's track
9. For the remainder of the SunSat's orbit, the beam is well above the LEO's orbit, now in the southern hemisphere.

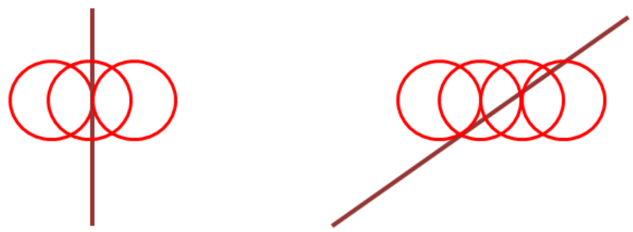
And so this process goes on and on, sidereal day after sidereal day.

Addressing the probability of the LEO getting hit

These diagrams only address the certainty of the beam intersecting the orbital path, *not* the satellite itself. We must further investigate (1) the duration in time that the intersection takes place, and, (2), what is the probability that the particular satellite is in this "kill zone" in those brief moments. We will see that the individual probabilities are indeed remote (on the order of 10^-4 per occurrence); however when we consider the hundreds of vulnerable satellites, the eight beams total, and the certainty of beams larger than 1km, these "miniscule" probabilities quickly snowball.

How long is the LEO orbit illuminated by the microwave beam?

A practical GEO based SSP system will illuminate at minimum a 1 km diameter area on the earth; and likely, much wider. At LEO this beam will not be significantly narrower than at the surface. We will use a 1 km diameter beam as our “kill zone”. For a polar LEO, the encounter will be briefest, as the beam sweeps across the orbital track perpendicular to it. For less-inclined LEO orbits, the encounter will be longer, as the beam drags more diagonally across the LEO’s orbit. The following diagram illustrates this.



To obtain an initial estimate of the amount of time the LEO is in jeopardy, let’s take the best-case scenario of the polar orbit; other orbits will only be worse.

Our GEO SunSat has a period of one sidereal day (86164.1 seconds). One revolution is 2*pi radians, so the angular velocity of the SunSat, and thus its beam, is:

$$\frac{2\pi}{86164.1} = 7.2921 * \ 10^{-5} \quad radians/sec \tag{7-1}$$

Let’s assume a typical LEO altitude of 500 km (radius 6880 km), and a circular orbit. We want to know how quickly our beam is sweeping through the sky at the LEO orbit radius. If we multiply our angular velocity by the LEO radius, we get

$$(7.2921 * \ 10^{-5} \, rad/sec) * (6880 \, km) = 0.502 \quad km/sec \tag{7-2}$$

If our “kill zone” is 1km wide, and it is sweeping at a rate of 0.5 km/s through the LEO orbit, that is a total encounter of approximately:

$$\frac{1 \, km}{0.5 \ km/sec} = 2 \, seconds \tag{7-3}$$

What is the probability the LEO was hit? We calculate its period from first principles as:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} = 5679 \, seconds \, (\sim 95 \, minutes) \tag{7-4}$$

We further assume a circular orbit and hence uniform speed. The probability that the satellite was hit will be:

$$\frac{2\ sec}{5679\ sec} = 3.52\ *\ 10^{-4} \quad (7\text{-}5)$$

We can confirm the veracity of this calculation by considering distance instead of time. The orbital circumference is:

$$\pi d = \pi(2r) = 43228\ km \quad (7\text{-}6)$$

The orbital speed is:

$$v = \sqrt{\frac{\mu}{a}} = 7.612\ km/sec \quad (7\text{-}7)$$

At the moment the orbit is first illuminated, if the LEO is within a swath of:

$$swath = (2\ \text{seconds}) * \left(7.612\frac{km}{s}\right) = 15.224\ km \quad (7\text{-}8)$$

It will fly through the SunSat beam. Finally we confirm:

$$probability\ of\ hit = \frac{swath}{circumference} = \frac{15.224\ km}{43228\ km} = 3.52\ *\ 10^{-4} \quad (7\text{-}9)$$

In the course of 1 sidereal day, we have two such “sweeps”, as depicted in the previous figure. Hence the probability, per sidereal day, of being hit is 2 * 3.52e-4, or **7.04e-4.**

It is worth noting that LEOs travel at about 7 km/sec. So at most, the LEO would be exposed for about 0.14 seconds. It is tempting to rationalize that an encounter of a fraction of a second isn’t worth the trouble. But the point is *it isn’t your satellite. You don’t own it. You’re not allowed to make life-or-death decisions with it.* If something does start malfunctioning on it, even if it isn’t your fault, the owner is going to unleash an army of lawyers on you.

Expanding to 470 LEOs and 8 microwave beams

Next, consider the estimate of 470 active LEO satellites. If the chances of a beam killing one LEO or the other are statistically independent, we can estimate the probability of *at least* one of the 470 getting fried in the course of a sidereal day, as 1 minus the probability of *none* of them getting fried.

$$1 - (1 - 7.04 * 10^{-4})^{470} = 0.282, or\ 28\ \% \quad (7\text{-}10)$$

Now things start to get interesting. We estimate that in the course of 1 sidereal day, there is a 28% chance of *just one* microwave beam killing at least one LEO. But wait, we don’t have one killer beam, we have 8 of them, to our 8 different earth stations. Again, we estimate the probability of at least one beam destroying a LEO is 1 minus the probability of none of them doing it.

$$1-(1-0.282)^8 \ = \ 0.929, or\ 93\ \% \qquad (7\text{-}11)$$

Now things are really dangerous. We're up to a 93% percent chance of one of our 8 beams killing a LEO *in the course of one day.*

Fine-tuning using actual data

To hone this estimate yet further, we turn to the UCS database mentioned earlier in the report [1]. The database is an excel spreadsheet. It gives many, but not all, orbital parameters. We get apogee, perigee, inclination, eccentricity, and period. These all give us the geometry of the orbit. It has approximately 450 active, operational LEO satellites, with orbital data. Because it does not have complete TLE-type data in it, orbits were circularized based purely on their orbital period. A tab-delimited version of the database was used in the actual simulation [2].

A C program was written, beam_intercept.c [2]. It inputs on the command line a single LEO orbital period, LEO inclination, SunSat ground station latitude, and beam width. Based on these parameters, The SunSat ground beam and the LEO circular orbit are calculated and the intercept points determined. From there, the SunSat beam is slewed based on the rotation of the earth. A precise time measurement, down to 1/10 of a second, is calculated of how long the LEO orbit is illuminated by the beam. For the following table, a 1 km-diameter kill zone was assumed.

A PERL script, process_database.pl [2], was written to "wrap" around this program. It reads the entries of the database, line by line, and calls the C program for each and every LEO. The hit probabilities output by the C program are tallied for all ~450 LEO satellites, and a net result presented. The results were in line with the rough estimate previously obtained:

Ground Station Latitude, deg.	**Locations**	**Number of LEO satellites threatened by SunSat beam**	**Probability of *at least one* LEO being hit, each sidereal day (assuming 1km diameter kill zone)**
40	Europe	446	39 %
39	West Virginia	446	34 %
31	Georgia, Mexico, Japan	450	31 %
27	Texas	452	30 %
25	Asia	453	30 %
-2	South America	457	28 %

This data shows a higher risk presented by higher-latitude beams, in spite of the fact that fewer actual LEOs are threatened by them. This was due to two factors. One, at higher latitudes, the "sweep speed" of the beam, in linear terms, is lower than at the equator. Also, the geometry of how the beams sweep across the LEO orbits is more slanted. Both factors resulted in longer-duration encounters.

But what if our beam is wider than 1 km diameter? Beam widths of 2 km to 15 km were recalculated. A Ground Station latitude of 31 degrees was used. In addition, the full binomial distribution was calculated [3]. Things get more interesting:

Beam width on ground (km)	**Binomial Distribution; probability of *X* LEO hits <u>per day</u> for just <u>one</u> beam at 31 degrees latitude**						
	No hits	**1 hit**	**2 hits**	**3 hits**	**4 hits**	**5 hits**	**6 or more hits**
1	69 %	25.6 %	4.7 %	0.6 %	0.1 %		
2	46.9 %	35.5 %	13.4 %	3.4 %	0.6 %	0.1 %	
3	32.0 %	36.5 %	20.8 %	7.9 %	2.2 %	0.5 %	0.1 %
4	21.8 %	33.3 %	25.3 %	12.8 %	4.9 %	1.5 %	0.5 %
5	14.8 %	28.3 %	27.1 %	17.2 %	8.2 %	3.1 %	1.3 %
7.5	5.6 %	16.3 %	23.4 %	22.4 %	16.1 %	9.2 %	7.0 %
10	2.1 %	8.3 %	15.9 %	20.4 %	19.5 %	14.9 %	18.7 %
15	0.3 %	1.8 %	5.2 %	10.0 %	14.5 %	16.7 %	51.6 %

Expanding your beam width out, to reduce the transmitter dish size, may seem like an easy way out. You get a smaller dish, but it comes at a great cost: much more LEO encounters requiring you to switch the thing off, possibly several times a day. So much for "24/7 baseload power"!

At the beam width of 3 km being considered so far, there's only a 1/3 chance you *won't* have to turn the beam off on a given day. There's about a 1/3 chance of turning it off *once*, and about a 1/3 chance of having to turn it off *two or more* times.

At 5 km things get worse. There's only a 15% chance per day you *won't* have to turn the beam off. There's a 30% chance of having to turn it off *three or more times*.

Beamwidths beyond 5 km get comedic. At 15km beam width, chances are better than 50/50 of *6 or more* encounters, *per day*.

MEO SunSats and, LEO-based Power Grid

This simulation was for GEO based SunSats, but neither MEO SunSats nor the LEO Power Grid proposed by Dr. Komerath [4] are immune to this problem.

For MEO SunSats, we still have 8 ground stations receiving a beam from well above the LEO altitude. The simulation would be greatly more complicated, having to calculate from where the beam is coming exactly. This does not impact the fact that there are still 450 LEO satellites whirling around below you, and that there are still 8 beams penetrating those orbits.

As for the Space Power Grid proposal, effects would likely be three times as bad. First there is the uplink beam from the surface to orbit, then the beam, or beams, from orbit-to-orbit, then the downlink beam to the surface. There's now a lot more opportunities for a LEO to fly through one of these beams.

Summary

SunSat systems pose a clear risk to the LEO satellite population. For the GEO SunSat simulation ran here, for a 3km beam, there is a 2 in 3 chance of a LEO being hit, per day. Some sort of real-time simulation and tracking system must be in place. This system must accurately predict in advance when interceptions will take place, and cycle the beam off for the LEO satellite to safely transit. This, of course, further erodes the promise of SSP as 24/7 baseload power. For beams beyond 5 km diameter, Ground Station personnel will have their hands quite full turning the thing on and off.

End Notes

1. Union of Concerned Scientists, Operational Satellite Database. Internet: http://www.ucsusa.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html Sep. 1, 2011 [Nov 2011]
2. Accompanying code: "beam_intercept.c", "process_database.pl", and UCS_Satellite_Database_9-1-11.tab; Also available in Author's ecelinsrv account.
3. Accompanying EXCEL spreadsheet, "LEO strikes.xlsx"
4. N. Komerath. ECE6390. Class lecture, Topic: "The Space Power Grid Approach to Space Solar Power." Georgia Institute of Technology, Atlanta, GA, Sep. 9, 2011. Available: http://streaming1.ece.gatech.edu/research/labs/propagation/ECE6390/notes/video/Lecture110908/ece_6390_20110908.wmv, [Nov 2011]. Notes available: http://www.propagation.gatech.edu/ECE6390/notes/SSP_SPGlecture20110908.pdf [Nov 2011].

Conclusions

SSP is a dangerous and unworkable concept, for the reasons outlined in the introduction and worked out in detail in this document.

The power densities on the earth are 10-100 times limits for the general public, and 3-30 times those for workers. One slip up could have disastrous consequences.

GEO based SSP is impractical due to photon pressure and excessive transmit dish sizes, not to mention, the burden of accurately aiming a dish 1/1000 to 1/100 of a degree.

MEO based SSP merely swaps these problems for others. A constellation of 18 SunSats, per orbital plane, would be required. Perhaps 3-4 orbital planes would be necessary to ensure total coverage. We're not talking about little sputniks, either, that's 54-72 structures equal to or double the mass of the ISS. They would be constructed in orbit, without the benefit of the now-gutted manned space program.

What is also not realistic is the MEO spacecraft steering this huge 20-meter, or more, dish. It must maintain pinpoint aim on the ground while flying overhead at over 10,000 MPH. Accuracy must be within a hundredth of one degree. Flawless execution is required. The consequences here are not somebody losing their MTV momentarily, their phone call getting dropped, or their internet going out. People could die.

As far as providing 24/7 baseload power, the devil is in the details. LEO avoidance, Ground Station maintenance, and rain fade at MMW all take their toll. An insufficient MEO constellation will have power outages near midnight.

A thorough analysis of FAA charts found no eligible locations to even put this Ground Station in Georgia or Texas. A similar analysis of other regions would probably be no more fruitful.

Power densities at the transmit dish are on the order of megawatts per square meter. If the dish doesn't melt outright, it will surely bend and flex as thermal expansion takes its toll. It will deviate greatly from a parabola and throw sidelobes everywhere.