Analysis, Modeling, Simulation and Experimentation

Space Solar Power Satellite Alternatives and Architectures

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Historical Background

- **Deploy large solar arrays in Earth orbit (typically geostationary) and beam power to receiver arrays on the ground**
  - Microwave beams most extensively studied, but there is an increasing interest in lasers
- **Concept proposed by Dr. Peter Glaser of Arthur D. Little Corp. in 1968 and studied by NASA and US Department of Energy during the 1970s**
  - Contractors included Boeing, Rockwell International, and Spectrolab
- **NASA and industry have studied the concept intermittently during the 1990s and early 2000s**
- **System sizes are huge (solar arrays several thousand meters across; power levels of thousands of megawatts)**
  - Due to the divergence of the microwave beam, a large amount of power must be collected to achieve an economically recoverable power density at the receiver array

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Sun Tower Solar Power Satellite

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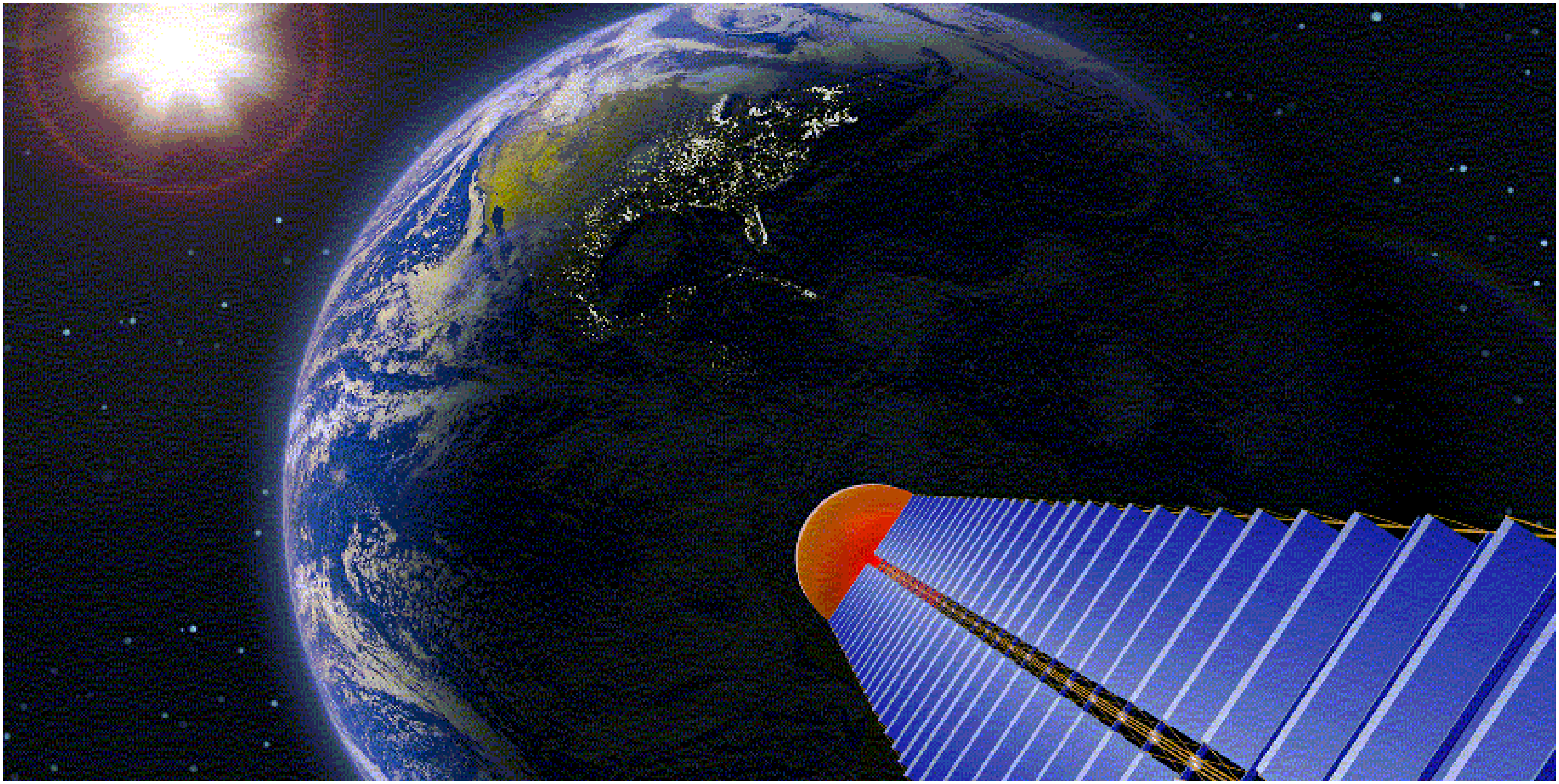

The Sun Tower is modular and scalable.

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Trade Studies: Assessment Criteria

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Trade Categories	Assessment Criteria														
Raw Materials Source	Accessibility (distance and required delta v)	Resource extractability (complexity of mining and refining operations)	Resource quality (concentration and purity)	Resource availability (mass)	Resource variety (type)	Space environment									
Manufacturing and Integration Location (may be separate)	Accessibility (distance and required delta v)	Space environment	Available in space infrastructure												
Deployment Location	Accessibility (distance and required delta v)	Possibility for permanent stationary terrestrial reception	Visibility from receiving location	Distance to Earth	Potential interference with other space systems	Potential synergy/ collocation with other space systems/missions	Space environment	Duration of blackout periods	Insolation	Need for active pointing/ orientation					
Space Transportation	Launch reliability	Payload mass per launch to destination	Achievable launch rate	Transfer time to destination	Total launch cost per payload mass	Available payload volume	Payload loads and accelerations	Required infrastructure	Scaleability	Return capability	Technology maturation	Safety	Environmental impact	Propellant deman	Required power
Energy Conversion	Conversion efficiency	Power conversion capacity per mass	Reliability	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation							
Energy Transmission	Transmission efficiency	Power transmission capacity per mass	Transmission accuracy and interference risk	Transmission intensity and ground safety	Required ground infrastructure and area	Total life cycle cost per mass	Need for terrestrial materials	Degradation	Reliability	Operational life	Technology maturation				
Energy Storage	Storage efficiency	Energy storage capacity per mass	Energy storage and release rate per mass	Reliability	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation						
Electronic Components	Memory sizes	Data rates	Reliability	Required power	Total life cycle cost per mass	Operational life	Degradation	Installed mass	Need for terrestrial materials	Technology maturation					
Electronics Architecture	Redundancy	Resilience	Reliability	Required power	Total life cycle cost per mass	Operational life	Degradation	Installed mass	Technology maturation						
Comand and Control Data Links	Bandwidth	Transmission range	Reliability	Required power	Transmission security and risk of interference	Installed mass	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation				
Attitude and Orbit Control	Mass fraction	Need for and type and mass of reactants/ propellants	Required power	Passive stability	Reliability	Operational life	Degradation	Scaleability	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation				
Structural Concept	Mass fraction	Operational life	Reliability	Degradation	Need for terrestrial materials	Scaleability	Element size and mass	Modularity	Stability	Technology maturation					
Thermal Management	Heat rejection capability per mass	Operational life	Reliability	Degradation	Installed mass	Required power	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation						
Concentrators	Mass fraction	Operational life	Reliability	Degradation	Need for terrestrial materials	Scaleability	Modularity	Shape complexity	Technology maturation						
Element Connection	Mass fraction	Operational life	Reliability	Degradation	Required power	Total life cycle cost per mass	Need for terrestrial materials	Scaleability	Stability	Technology maturation					
System Configuration	Redundancy	Resilience	Reliability	Mass fraction	Required power	Total life cycle cost per mass	Element size and mass	Scaleability	Technology maturation						
Manufacturing, Assembly and Maintenance Operations	Number of needed crew per installed power capability	Number of needed robots per installed power capability	Logistics and support requirements	Reliability	Total life cycle cost per installed power capability	Required infrastructure	Crew safety (mission risks and need for EVAs)	Number of different operational locations	Size, mass and complexity of robots	Mission duration for human crew	Technology maturation	Resilience	Deployed architecture mass		

Key	
	Potential Showstopper
	Highly Critical Decision Driver
	Critical Decision Driver
	Tiebreaker Only

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Boeing Trade Studies: Ratings of Options

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Trade Categories	Trade Options													
Raw Materials Source	Earth	Moon	Near Earth Objects	Phobos/ Deimos										
Manufacturing and Integration Location (may be separate)	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (GEO)	Molniya Earth Orbit	Earth-Moon Libration points and halo orbits	Earth-Sun Libration points and halo orbits	Lunar surface	Earth surface	Mars orbit			
Deployment Location	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (GEO)	Molniya Earth Orbit	Earth-Moon Libration points and halo orbits	Earth-Sun Libration points and halo orbits	Lunar surface					
Space Transportation	Launch vehicles and spacecraft with chemical propulsion (expendable and reusable)	Spacecraft with solar electric (electrostatic/ electrothermal/ electromagnetic) propulsion (in space only)	Spacecraft with solar thermal propulsion (in space only)	Solar/electric/ magnetic sails (in space only)	Tethers (mechanical/ electrodynamic) (in space/upper atmosphere only)	Electromagnetic mass drivers/rail guns and catchers	Lofstrom launch loop/space cable	Launch ring/ slingatron	External laser/ microwave propulsion	Light gas guns	Space elevator/ orbital ring	Space fountain/ orbital tower	Spacecraft with nuclear fission propulsion (thermal/electric/ pulsed detonation)	Spacecraft with fusion/ antimatter propulsion
Energy Conversion	Photovoltaic	Solar dynamic/ thermodynamic/ magnetohydrodynamic	Thermionic/ thermoelectric	Solar pumped laser/maser	Signal processing solutions	Nanofabricated rectenna	Optical rectenna	Rapidly ionizing plasma	Optical resonators	Shocked photonic crystals	None (reflection only)			
Energy Transmission	Laser (visible/ Infrared)	Microwave/maser	Physical transfer of energy storage media	Cable (in GEO only)	Focused reflection	Relay satellites/ mirrors								
Energy Storage	Supercapacitors	Superconducting magnetic	Reversible fuel cells	Batteries	Thermal storage/phase change material	High energy density matter	Flywheels	None (real time power transmission only)						
Electronic Components	Standard space qualified	Nanotechnology	Radiofrequency connections	Commercial off the shelf	Superconductors	Optical								
Electronics Architecture	Distributed	Centralized												
Comand and Control Data Links	Radiofrequency	Laser (visible/Infrared)												
Attitude and Orbit Control	Reaction control systems	Electromagnetic torque coils/rods	Electromagnetic tethers	Permanent magnets	Gyros/momentum wheels	Radiometer spin/solar sails	Gravity gradient	Spin stabilization						
Structural Concept	Solid members	Rigidized inflatables	Tethers											
Thermal Management	Passive cooling	Active cooling	None											
Concentrators	Reflective	Diffractive	Refractive	None										
Element Connection	Rigid attachements	Articulated joints	Free flying elements											
System Configuration	Functionally integrated identical modules	Monolithic elements with separate functions	Distributed elements with separate functions											
Manufacturing, Assembly and Maintenance Operations	Purely Human	Human/robotic cooperation	Human tended robotic	Purely robotic with local human supervision	Purely robotic with remote human supervision	Self replicating intelligent autonomous robots								

Key	
	Baseline (Most Preferred) Option
	Highly Preferred Option
	Less Preferred Option
	Least Likely Option

Each trade will be assessed in terms of performance and cost

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Boeing Trade Studies: Ratings of Options

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- **Highly Preferred Option**
- **Less Preferred Option**
- **Least Likely Option**

Initial focus is on major drivers of system design and cost

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Model Architecture for Space Solar Power & Lunar Colonization

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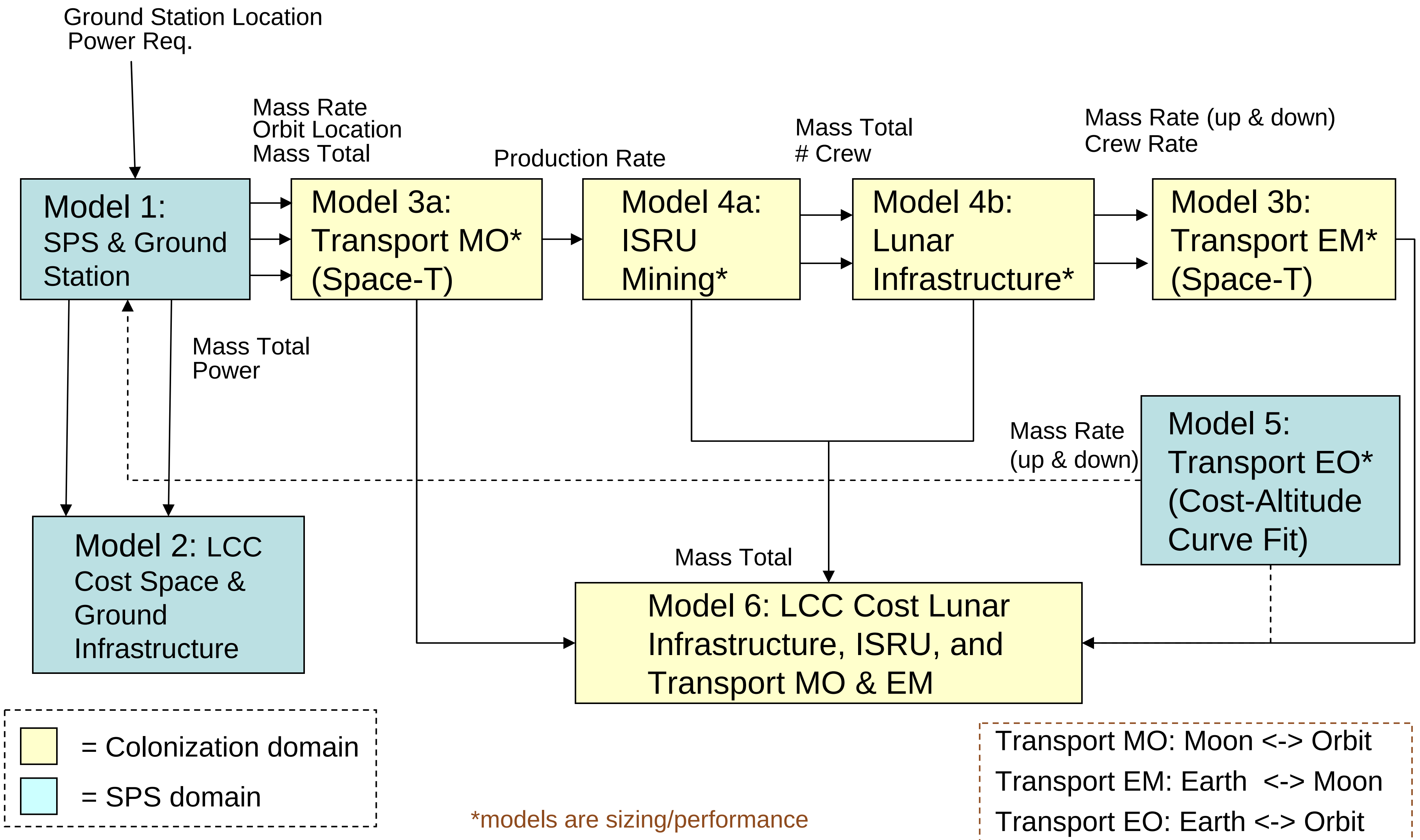

*models are sizing/performance

Transport MO: Moon <-> Orbit
Transport EM: Earth <-> Moon
Transport EO: Earth <-> Orbit

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Model 1: Size of Receiver Array

$$\frac{D_t\, D_r}{\lambda\, x} = 2.44$$

where

D_t = diameter of transmitting antenna

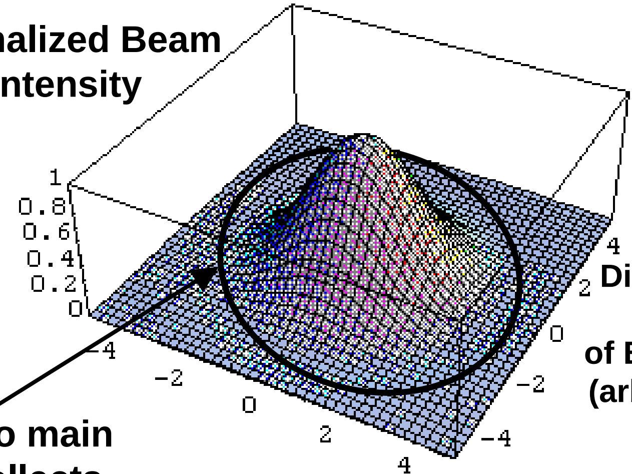
D_r = diameter of receiving antenna

λ = wavelength of beam

x = distance between antennas (determined by orbit)

Note: parameters must be in the same units; e.g., all in meters.

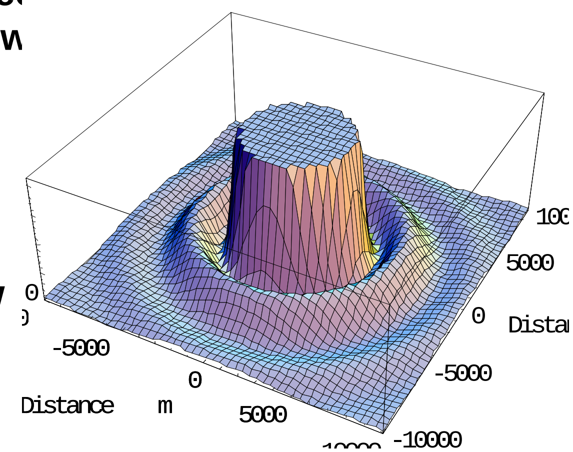
Normalized Beam Intensity



Distance from Center of Beam Pattern (arbitrary units)

Array sized to main beam lobe collects 84% of total pow

Vertical scale expanded to show sidelobes



For a given beam wavelength, transmitting antenna size, and distance to receiver, beam diameter at the receiver is independent of amount of power transmitted.

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Model 1: Calculation of Beam Intensity

$$I_0 = \frac{\pi P_t}{4} \left\{ \frac{D_t}{\lambda x} \right\}^2$$

where

I_0 = peak beam intensity

P_t = transmitted power

D_t = diameter of transmitting antenna

λ = wavelength

x = distance between antennas

Typically, bean intensity will be a requirement determined by physical and environmental constraints, and the transmitting antenna will be sized to focus the energy to this intensity.

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Model 2: Cost Model Process Flow Overview

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Space Solar Power Architecture Assessment

- Power consumption
- Area of ground space available
- Orbit

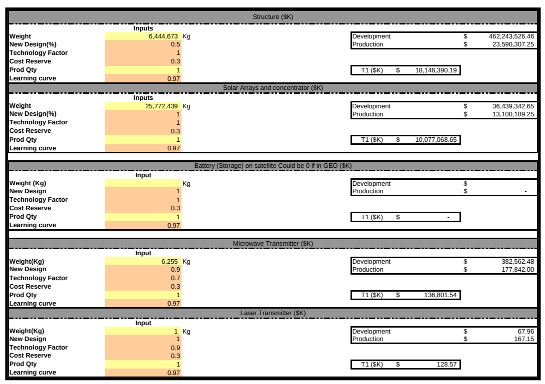
Design Sheet Space Solar Power Sizing Model

Output to cost model

- Element masses
- Ground battery power storage needed
- Receiving antenna area

Cost Model Input Sheet

- Input element mass from design sheet
- O&S support



Structure ($K)

Inputs					
Weight	6,444,673	Kg	Development	$	462,243,526.46
New Design(%)	0.5		Production	$	23,590,307.25
Technology Factor	1				
Cost Reserve	0.3				
Prod Qty	1		T1 ($K)	$	18,146,390.19
Learning curve	0.97				

Solar Arrays and concentrator ($K)

Inputs					
Weight	25,772,439	Kg	Development	$	36,439,342.65
New Design(%)	1		Production	$	13,100,189.25
Technology Factor	1				
Cost Reserve	0.3				
Prod Qty	1		T1 ($K)	$	10,077,068.65
Learning curve	0.97				

Battery (Storage) on satellite Could be 0 if in GEO ($K)

Input					
Weight (Kg)	-	Kg	Development	$	-
New Design	1		Production	$	-
Technology Factor	1				
Cost Reserve	0.3				
Prod Qty	1		T1 ($K)	$	-
Learning curve	0.97				

Microwave Transmitter ($K)

Input					
Weight(Kg)	6,255	Kg	Development	$	382,562.48
New Design	0.9		Production	$	177,842.00
Technology Factor	0.7				
Cost Reserve	0.3				
Prod Qty	1		T1 ($K)	$	136,801.54
Learning curve	0.97				

Laser Transmitter ($K)

Input					
Weight(Kg)	1	Kg	Development	$	67.96
New Design	1		Production	$	167.15
Technology Factor	0.9				
Cost Reserve	0.3				
Prod Qty	1		T1 ($K)	$	128.57
Learning curve	0.97				

Cost Model CERs

- Based on historical data:
  - Unmanned Space System Cost Model (USCM8)
  - GPS IIF for PM,SE & AI&T

Architecture LCC

- Development cost
- Production cost
- Operations cost

Design Sheet mass outputs, architecture structure, and model inputs are used to determine element costs.

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Model 2: Notional SSP Cost Modeling Assumptions

- Level 0 Analysis
- Constant year dollars 2008
- Technology assumed to be mature to 2028
- 97% learning curve for production
- 30 Year mean mission duration (MMD) for each satellite
- Mass in kg
- Estimate includes Spacecraft, Rectenna, Systems Engineering (SE), Program Management (PM), Assembly Integration &Test (AI&T), Operations &Support (O&S) and ground battery
- Baseline design includes microwave technology for transmitter
- O&S Includes spares and support on ground for 1 year
- If launched from Moon or Earth, infrastructure, materials, factory for production already in place
- On-base support provided for ground base
- Initial spares 10% factor per space vehicle production
- 12 Robonauts included in production cost for maintenance to be launched with satellite
- Sustaining Engineering 10% of yearly SE dollars

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Model 5: Earth-to-Orbit Transportation

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- **The SSPS model for launch costs uses a baseline $/kg to LEO, then scales that up depending on the target orbit input by the user.**
  - Meant as a feasibility study tool for SSP satellites
  - Launch cost model was designed to be as independent as possible of the launch method
  - Still captures extra launch cost associated with higher energy orbit locations
- **Simple table lookup for various orbit locations**
- **Launch_Factor = t_factor(Launch_Satellite_Location)**
- **Launch_$perKg_atLocation = Launch_LEO_$perKg / Launch_Factor**

:Table	t_Trajectories
t_Location >	t_factor
LEO	1
Molniya	0.45
MEO	0.4
GPS	0.27
GEO	0.2

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Military Mission Needs: Recent Developments

- **From the NSSO Report:**

  Recommendation: *The SBSP Study Group recommends that the U.S. Government should sponsor a formally funded, follow-on architecture study with industry and international partners that could lead to a competition for an orbital demonstration of the key underlying technologies and systems needed for an initial 5-50 MWe continuous SBSP system.*

- Discussions at the NSSO SBSP meeting in 9/07 emphasized power levels of 5-15 MW at forward military bases having available land parcels of ~1000 meters in width to support a rectenna array

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Civil Government Installation: Example – Amundsen-Scott South Pole Station

- **Characteristics (Source: http://www.nsf.gov/od/opp/support/southp.jsp):**
  - Diurnal cycle is annual, i.e., 6 months of daylight, 6 months of darkness
  - Elevation: 2,835 meters (9,306 feet)
  - Temperature range: -13.6° C to -82.8° C. Annual mean is -49° C; monthly means vary from -28° C in December to -60° C in July. Average wind is 10.7 knots (12.3 miles per hour); peak gust recorded was 48 knots (55 miles per hour) in August 1989.
  - Snow accumulation is about 20 centimeters (6-8 centimeters water equivalent) per year, with very low humidity.
- **Population of Station:**
  - Summer: 150 people
  - Winter: 50 people
- **Power consumption scaled from military bases at 3 kW/person**
  - Summer: 150 people x 3 kW/person = 450 kW
  - Winter: 50 people x 3 kW/person = 150 kW

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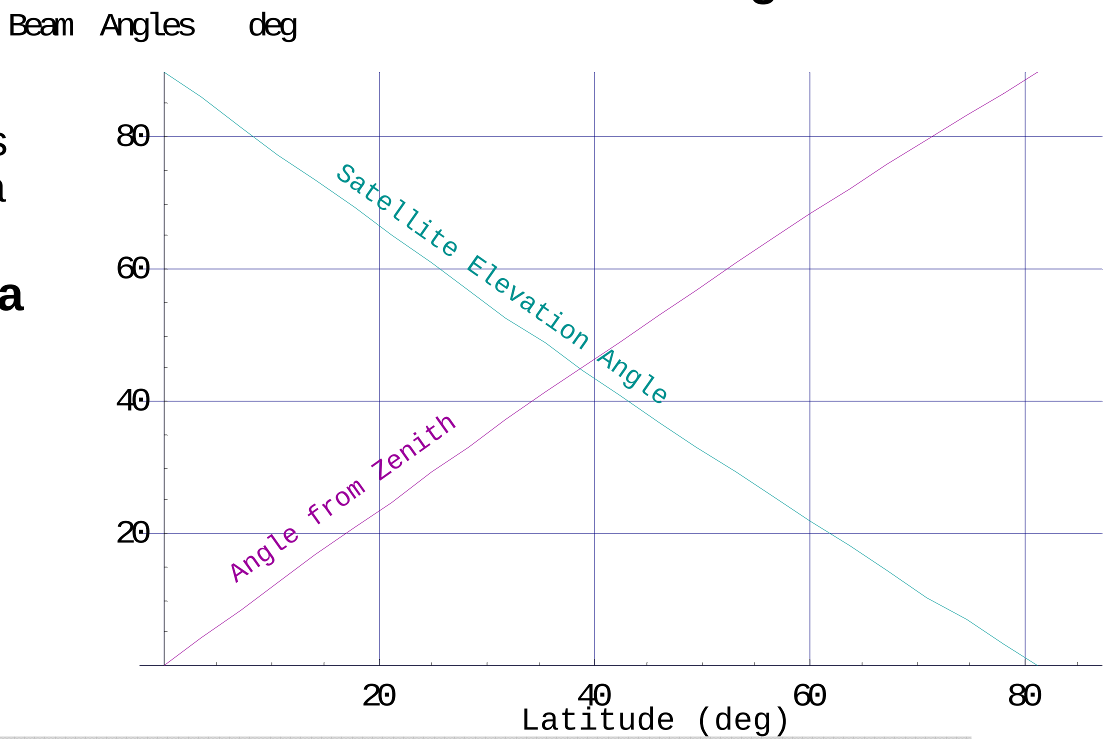
Is SSP Feasible for a South Pole Base?

- **GEO satellites are not visible at the poles, and are below the horizon for any latitude poleward of ± 81°**
  - LEO and MEO satellites will not be visible at the poles for low orbital inclinations
- **Molniya orbits have been used for communications access to high latitudes**
  - Highly elliptical with apogee over a pole
  - Our analysis suggests that access times from a Molniya satellite to a polar station would be good
- **Microwave transmitting antenna would be impractically large, for the amount of power delivered**
- **Laser power beaming would have to be used.**



The power requirements of a polar research facility can be met by a small solar power satellite in a Molniya orbit using laser power transmission.

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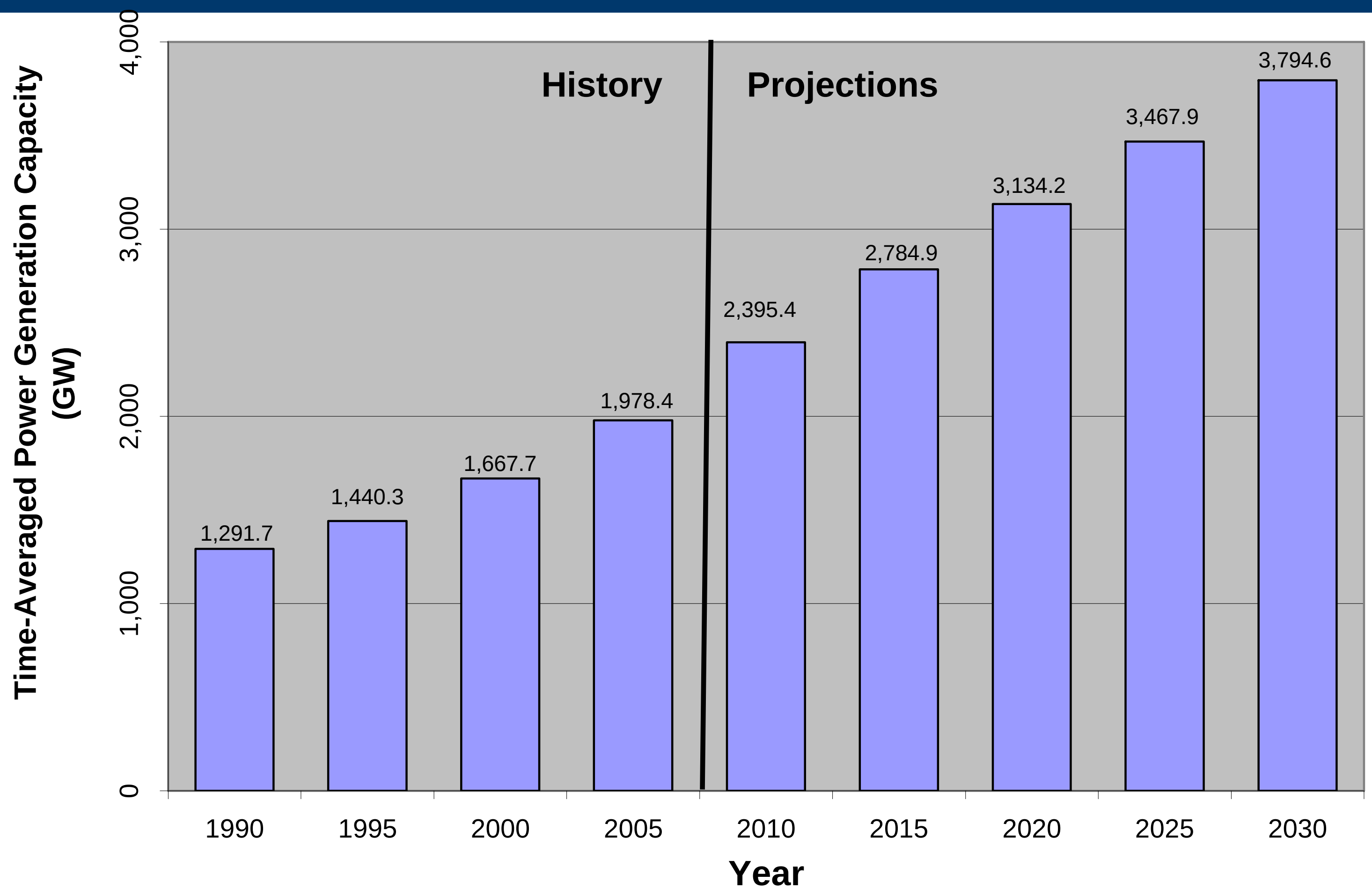
Time-Averaged Global Electric Power Generation Capacity



Data Source: U.S. Energy Information Administration, Report #:DOE/EIA-0484(2008), September 2008.

To meet 10% of future global electricity requirements, 20 GW of SSP capacity must be deployed per year. Our model computes mass launch requirements from this.

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Historic SPS Mass vs. Power For Several Architectures: Logarithmic Plot

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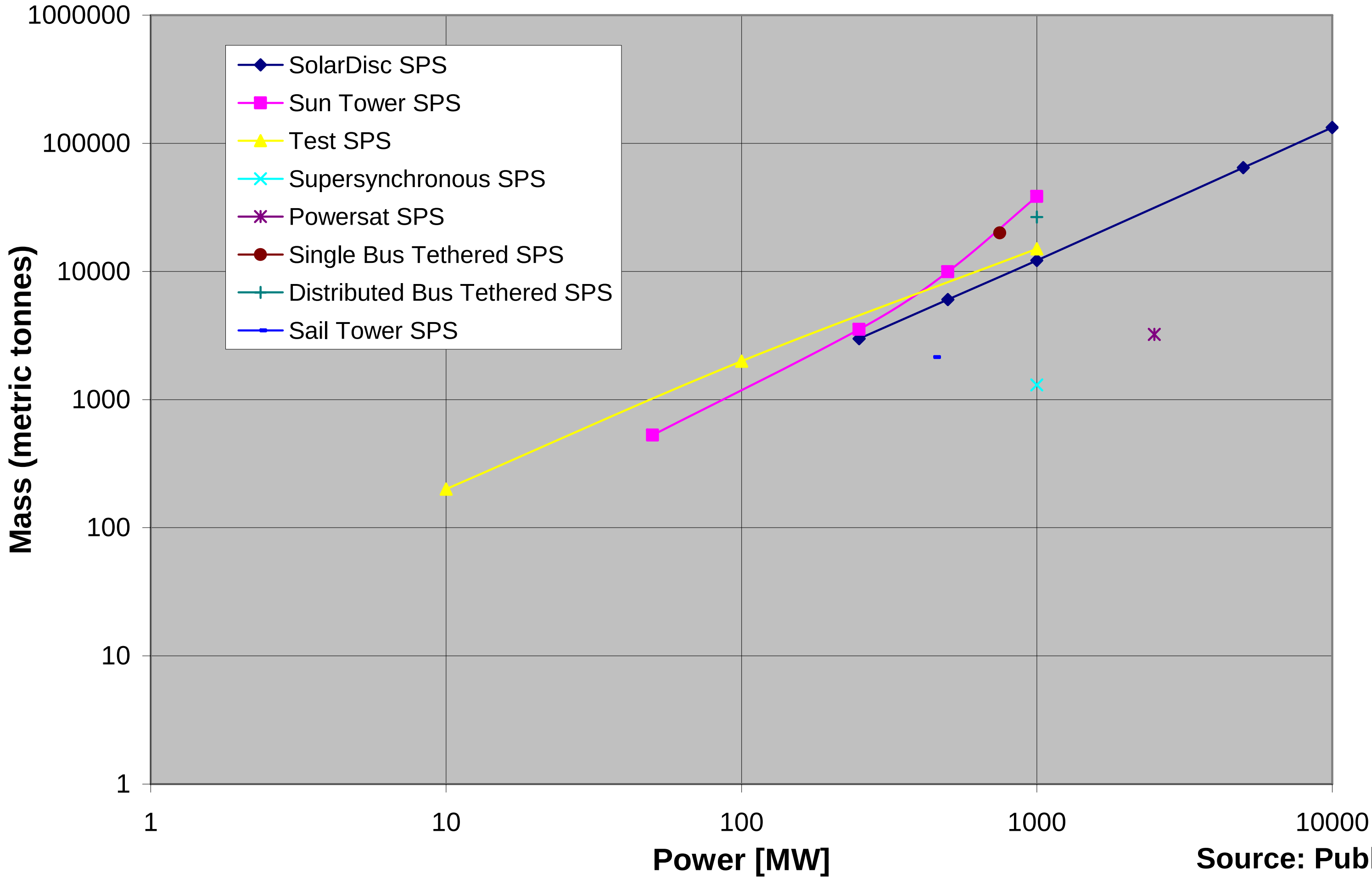

Source: Public Domain

Mass of an SPS is roughly proportional to the power level.

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Historic SPS Mass vs. Power For Several Architectures: Linear Plot

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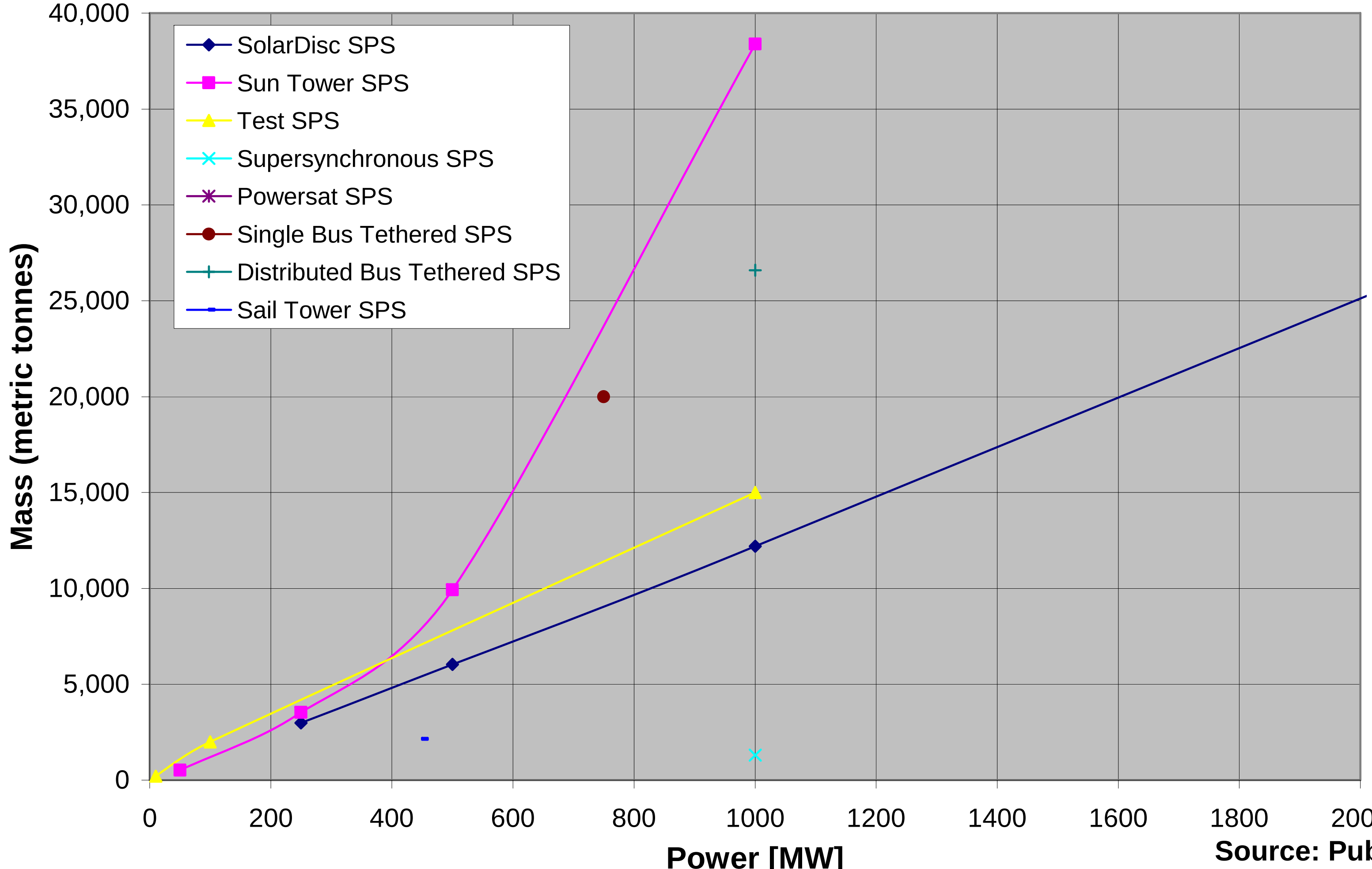

Source: Public Domain

On an expanded scale, nonlinearities in SPS mass are seen.

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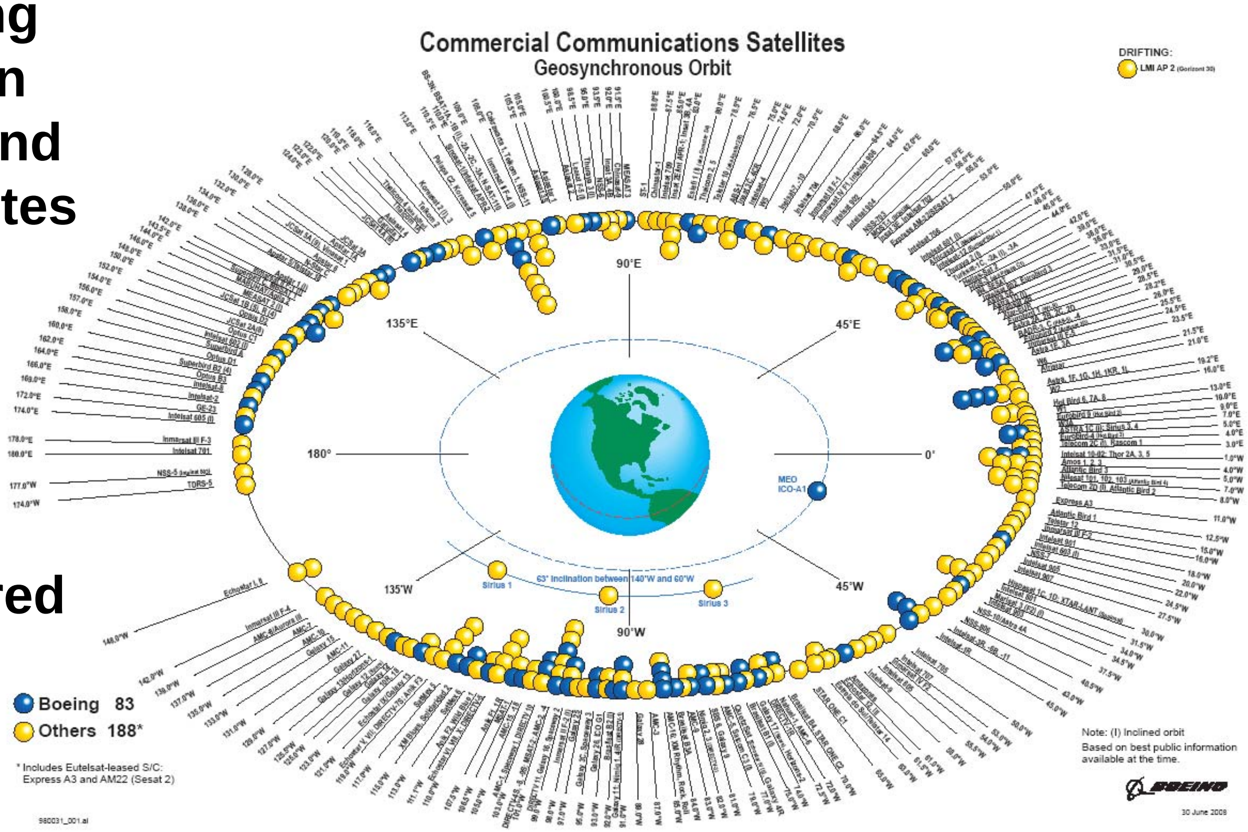
Geostationary Orbital Slot Allocation

- **A total of 271 commercial communications satellites in the geostationary belt are shown**
  – Actual total could be higher if government satellites are included
- **The feasibility of sharing of the GEO belt between solar power satellites and communications satellites must be studied**
  – Issues to be considered include determining the spacing required
- **SPS's that cease to function must be repaired or disposed of in a "graveyard orbit"**
  – Their materials may be salvageable for future SPS's



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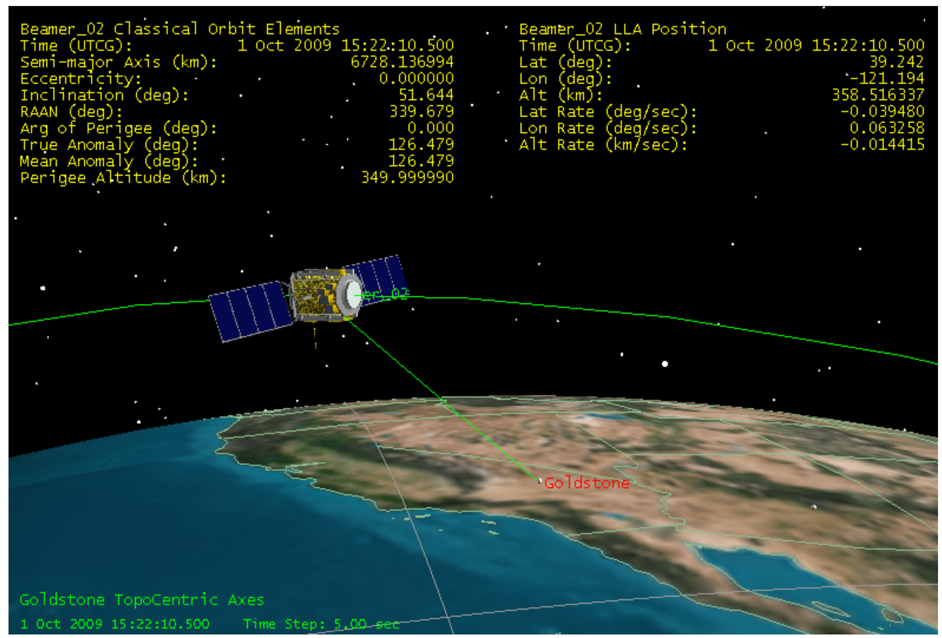
Low Earth Orbit (LEO) Power Beaming

- **Example orbit: 350 km circular, 51.6° inclination – ISS-like, so results traceable to ISS or Shuttle-to-ground demos**
- **Illustration shows access to Goldstone**
- **Satellite accesses ground station for 5 to 10 minutes at a time during 8 of the ~16 daily orbits if no minimum elevation angle constraint is set**
- **For 10° minimum elevation angle, then the accesses are 6 minutes each with two accesses per day**
- **For 30° minimum elevation angle, there are still two satellite accesses per day, lasting only 2½ minutes each**



A low Earth orbit at ISS altitude may provide sufficient ground station access time for demos, but many would have to be deployed to beam power continuously to customers.

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Medium Earth Orbit (MEO) – Coverage of a Single Satellite

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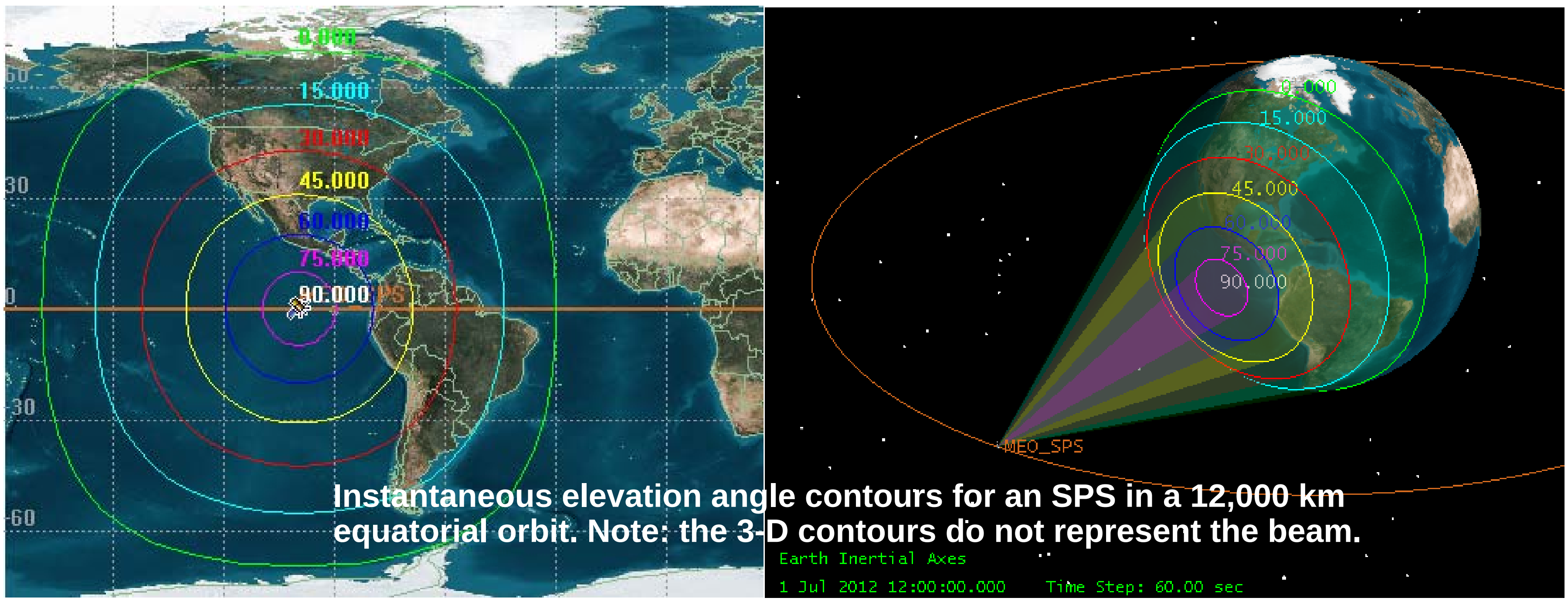
- **An equatorial MEO SPS in a 12,000-km circular orbit (6-hour 53-minute orbital period) may be able to serve tropical and lower temperate latitudes**
- **Satellite would be in sunlight continuously around the solstices**
- **Around the equinoxes, the satellites are in eclipse for 46 minutes during each orbit**
- **From the lower left figure, the satellite would appear to cover middle latitudes such as the continental US. However, the elevation angle contours shown are an instantaneous snapshot of a non-geostationary satellite, so access times could be relatively short.**



Instantaneous elevation angle contours for an SPS in a 12,000 km equatorial orbit. Note: the 3-D contours do not represent the beam.

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MEO Orbit Coverage Durations: One 12,000-km Equatorial Satellite

- **Goldstone (35.3° latitude): 2 or 3 passes per day, 3 hours 29 minutes over the horizon (neglecting mountains), 1 hour 22 minutes at elevation angles ≥ 30°.**
- **Mid-Nevada Rectenna (40° latitude): 2 or 3 passes per day, 3 hours 23 minutes over the horizon (neglecting mountains), 51 minutes at elevation angles ≥ 30°.**
- **Above 42.6° latitude, the satellite is never above a 30° elevation angle**

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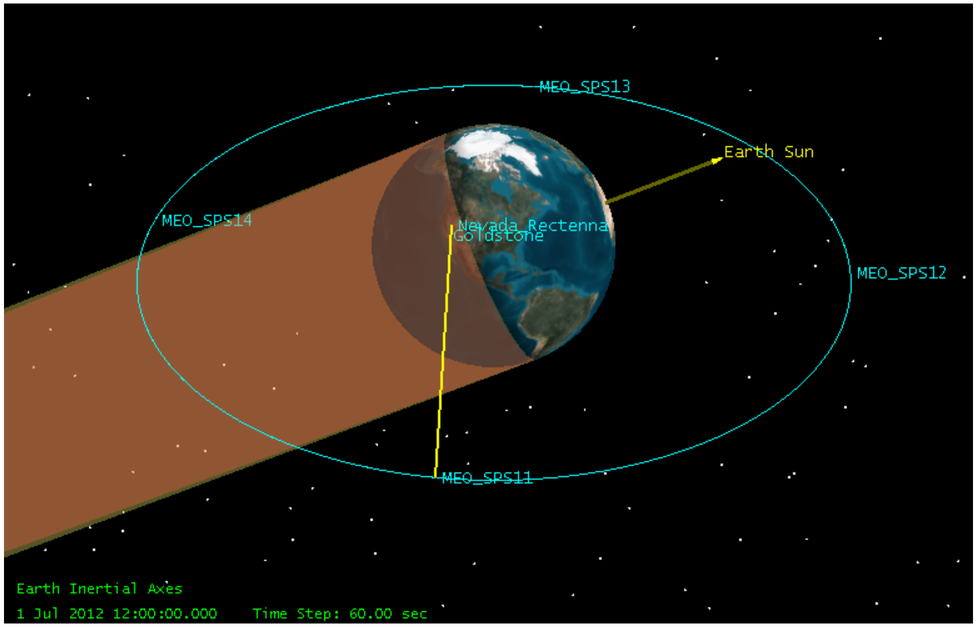
MEO Orbit Coverage Durations: Four 12,000-km Equatorial Satellites (Evenly Spaced)

- **Goldstone (35.3° latitude): at least one satellite (sometimes two) is over the horizon at all times**
- **Goldstone (elevation angles ≥ 30°): 9 or 10 passes per day, 1 hour 22 minutes per pass with about 1 hour 3 minutes gap between passes, i.e., 13 hours 35 minutes access per day**
- **Mid-Nevada Rectenna (40° latitude): at least one satellite (sometimes two) is over the horizon at all times**
- **Mid-Nevada Rectenna (elevation angles ≥ 30°): 9 or 10 passes per day, typically 51 minutes per pass with about 1 hour 34 minute gap between passes; i.e., about 8 hours 29 minutes access per day total**



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Molniya Orbits Can Beam Power to Polar Regions

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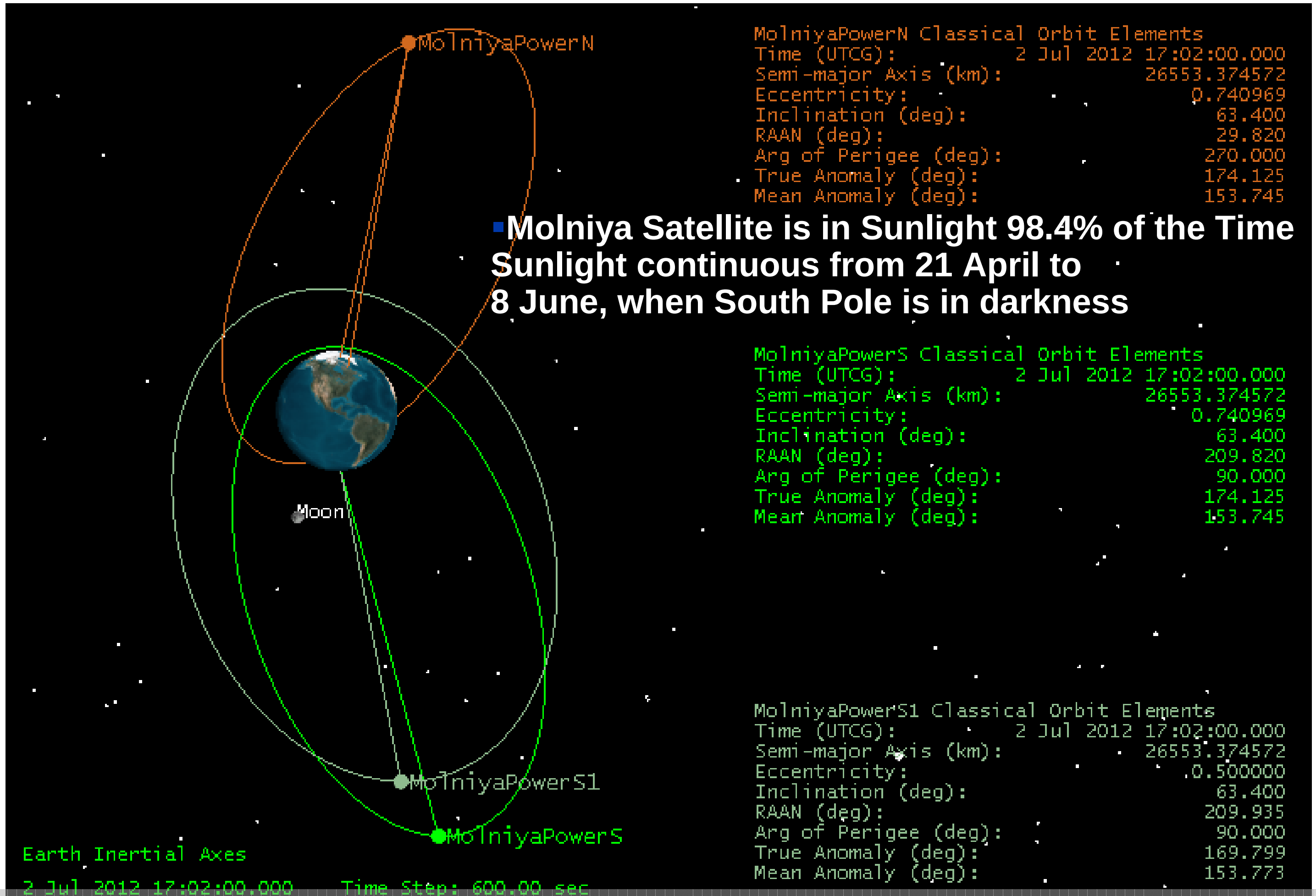

- **Molniya Satellite is in Sunlight 98.4% of the Time Sunlight continuous from 21 April to 8 June, when South Pole is in darkness**

Highly elliptical Molniya orbits can access polar regions, which are inaccessible to geostationary satellites.

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Molniya Orbit Ground Tracks: Access to Ground Stations Shown in Bold

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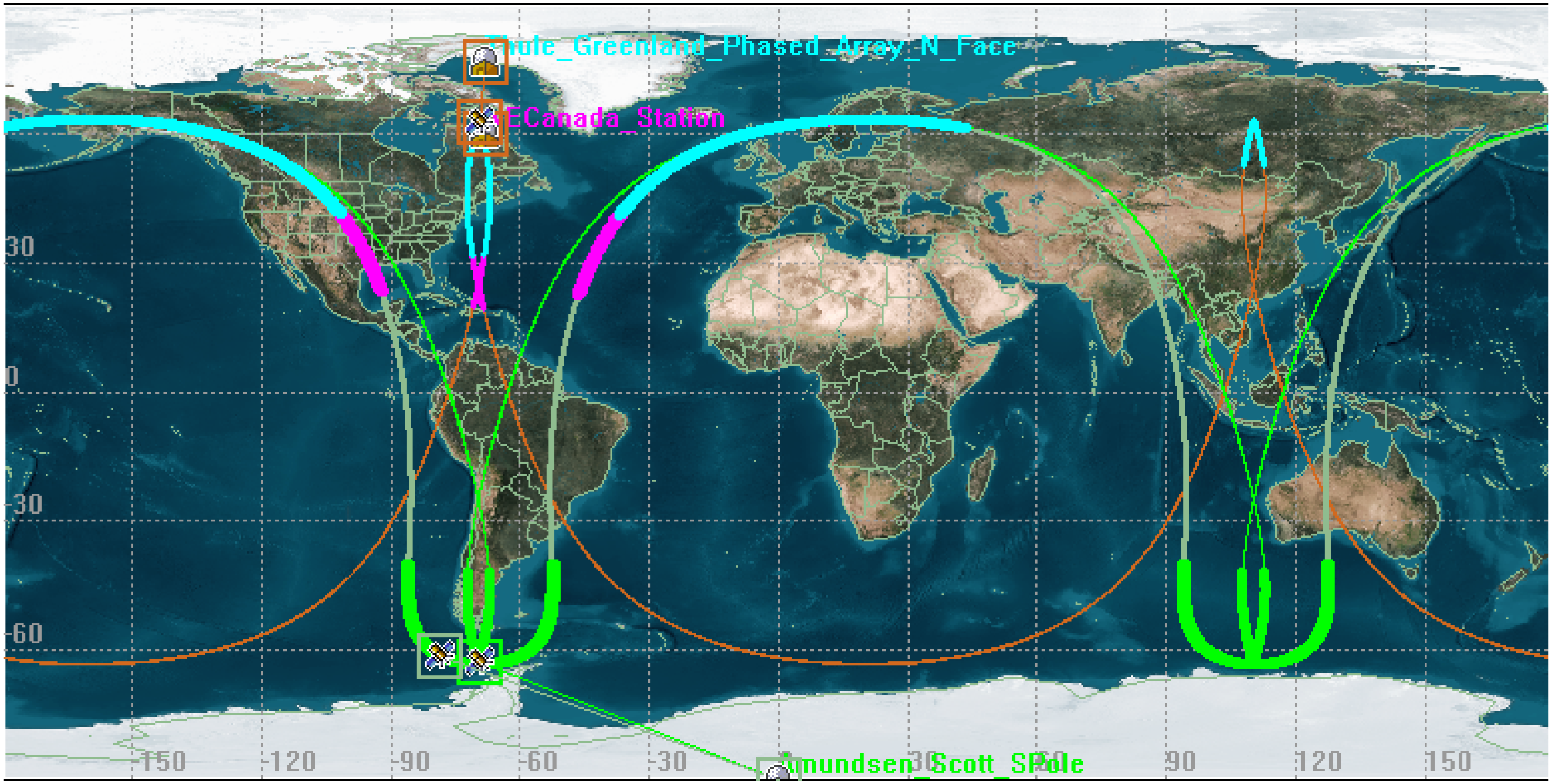

Molniya orbits can support power beaming to scientific research facilities and military bases in polar regions.

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Molniya Orbit Over South Pole

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- **An orbit of 39,851 km x 500 km was considered to supply power to the Amundsen-Scott South Pole Research Station**
- **A 20-day propagation was performed**
  - Access durations were considered for a satellite at least 30° over the horizon as seen from the South Pole
- **As seen in the table, the satellite makes two passes per day, and is visible for 8.8 hours per pass (out of 12 hours per orbit) for a duty cycle of 73%**

30 deg min elevation angle, 63.4 deg inclination, 12-hour Molniya

MolniyaPowerS-To-Amundsen_Scott_SPole

Access #	Start Time (UTCG)	Stop Time (UTCG)	Duration (hr)
1	7/1/12 13:36	7/1/12 22:21	8.758
2	7/2/12 1:34	7/2/12 10:19	8.758
3	7/2/12 13:31	7/2/12 22:17	8.758
4	7/3/12 1:29	7/3/12 10:14	8.758
5	7/3/12 13:27	7/3/12 22:12	8.758
6	7/4/12 1:24	7/4/12 10:10	8.758
7	7/4/12 13:22	7/4/12 22:08	8.758
8	7/5/12 1:20	7/5/12 10:05	8.758
9	7/5/12 13:18	7/5/12 22:03	8.758
10	7/6/12 1:15	7/6/12 10:01	8.758
11	7/6/12 13:13	7/6/12 21:59	8.758
12	7/7/12 1:11	7/7/12 9:56	8.758
13	7/7/12 13:09	7/7/12 21:54	8.758
14	7/8/12 1:06	7/8/12 9:52	8.758
15	7/8/12 13:04	7/8/12 21:50	8.758
16	7/9/12 1:02	7/9/12 9:47	8.758
17	7/9/12 13:00	7/9/12 21:45	8.758
18	7/10/12 0:57	7/10/12 9:43	8.758
19	7/10/12 12:55	7/10/12 21:41	8.758
20	7/11/12 0:53	7/11/12 9:38	8.758

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Geostationary Orbits

- **Geostationary orbits (GEO) have an altitude of 35,786 km and are circular (or nearly so) and have an inclination of 0° (or nearly so), that is they are equatorial**
- **Minimizes scanning losses of satellites in lower orbits that must continuously slew their beam to maintain power transmission to the ground site**
- **Launch to geostationary orbit from Earth is more costly than low orbits, but may actually be less costly than some medium Earth orbits because the latter may have higher inclinations**
- **The main disadvantage of GEO is that the divergence of the beam over such a long distance drives SSP system sizes up**
  - GEO orbits have usually been considered the default orbits for solar power satellites, though more recent studies have considered lower orbits to achieve smaller system sizes and lower costs to first power

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Geostationary Orbit Shown to Scale

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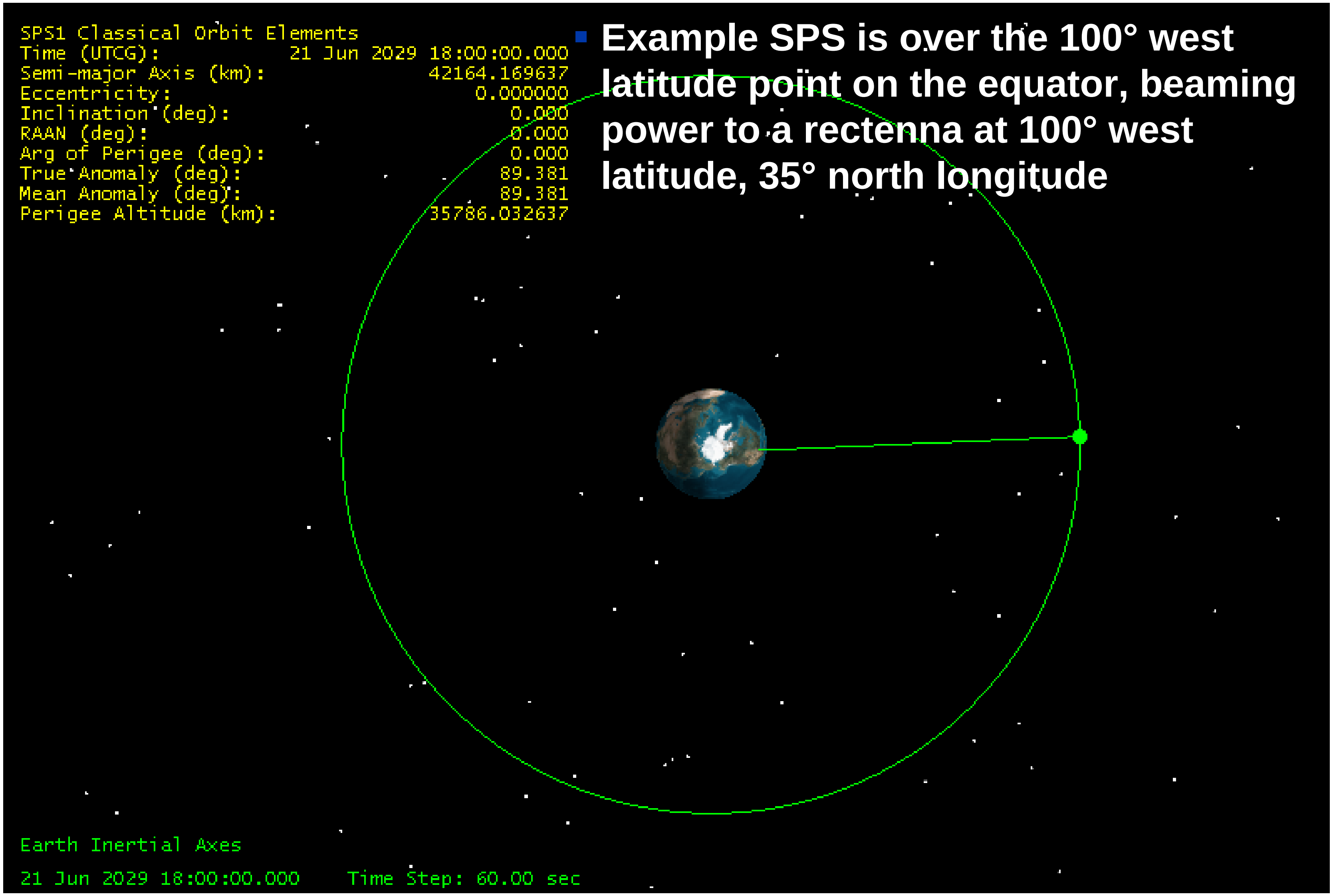
- **Example SPS is over the 100° west latitude point on the equator, beaming power to a rectenna at 100° west latitude, 35° north longitude**



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Coverage Limits of GEO Satellites

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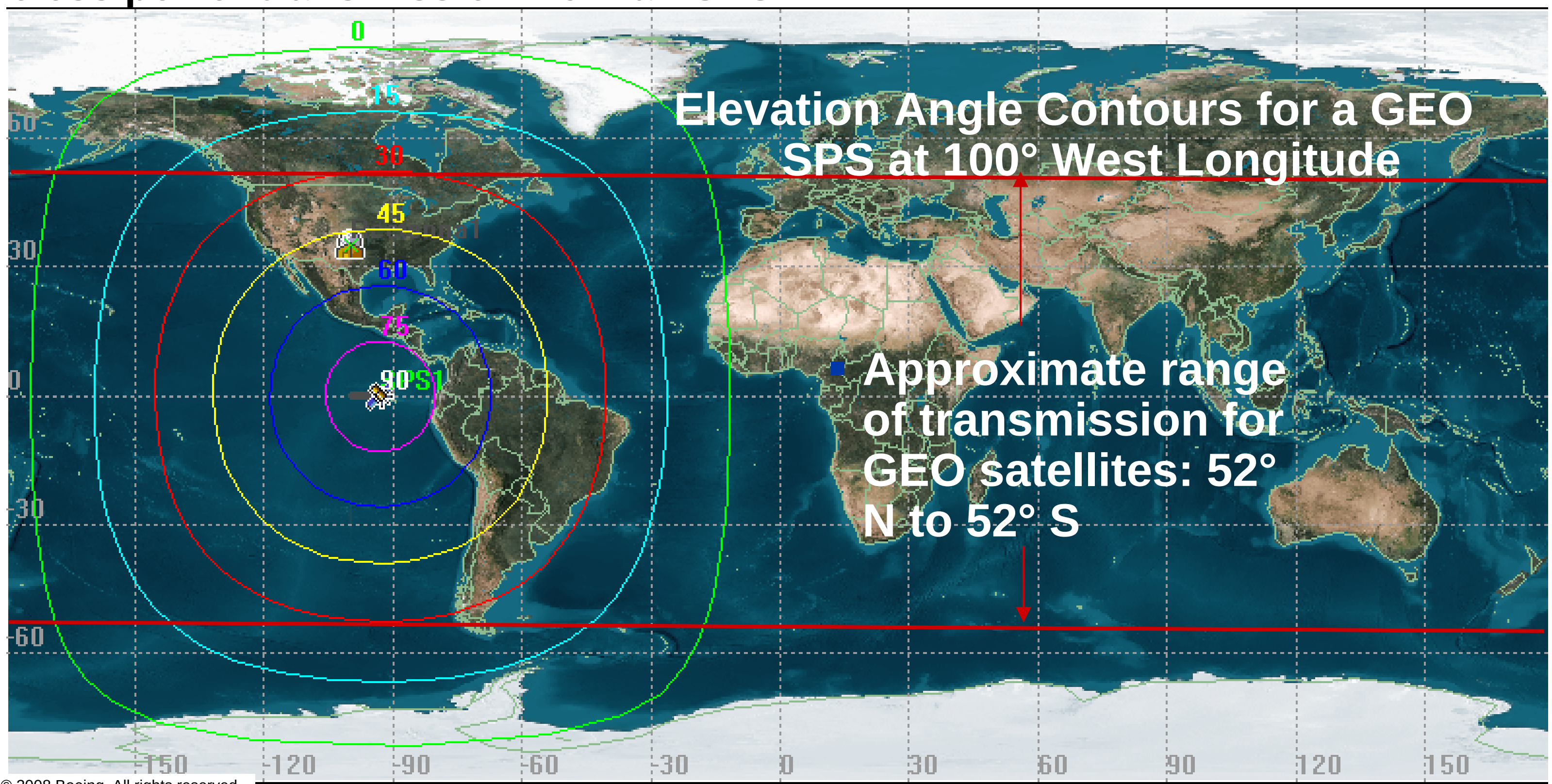
- **If orbital slots are available at the appropriate longitudes, GEO SPS's can beam power to any longitude**
- **The latitude limits encompass much of the world's populated area, but beaming power from GEO is ultimately limited by elevation angle constraints**
- **30° may be the minimum practical elevation angle (angle over the horizon) for wireless power transmission from an SPS**



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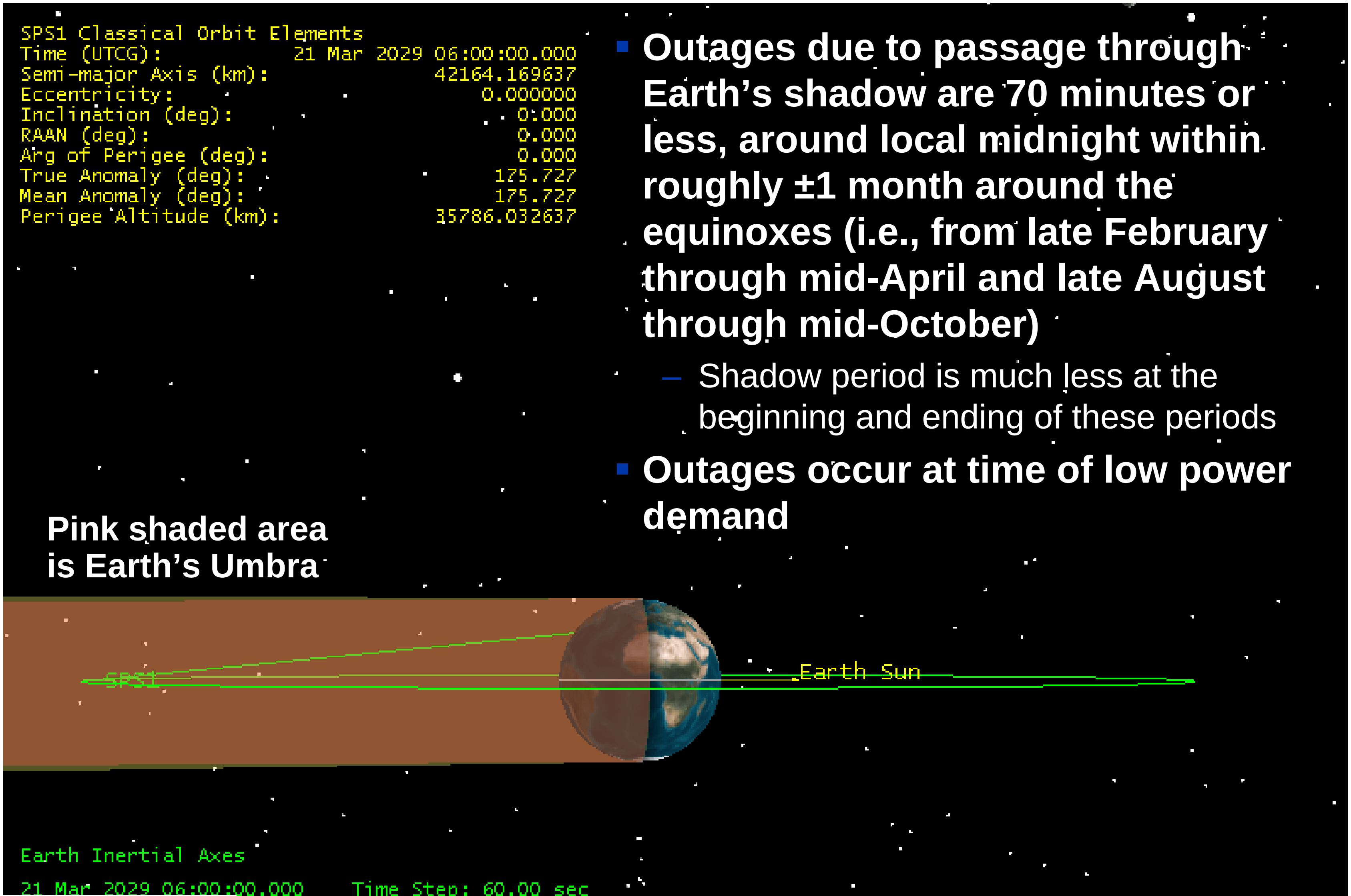
GEO SPS is in Shadow Briefly Around Equinoxes

- **Outages due to passage through Earth's shadow are 70 minutes or less, around local midnight within roughly ±1 month around the equinoxes (i.e., from late February through mid-April and late August through mid-October)**
  - Shadow period is much less at the beginning and ending of these periods
- **Outages occur at time of low power demand**



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Possible Locations for Initial GEO SPS's

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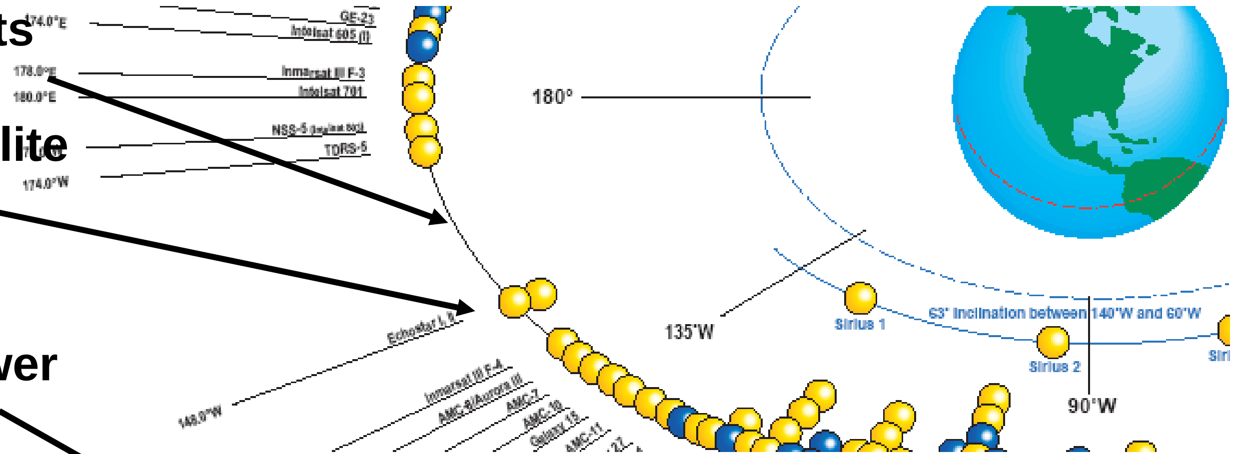
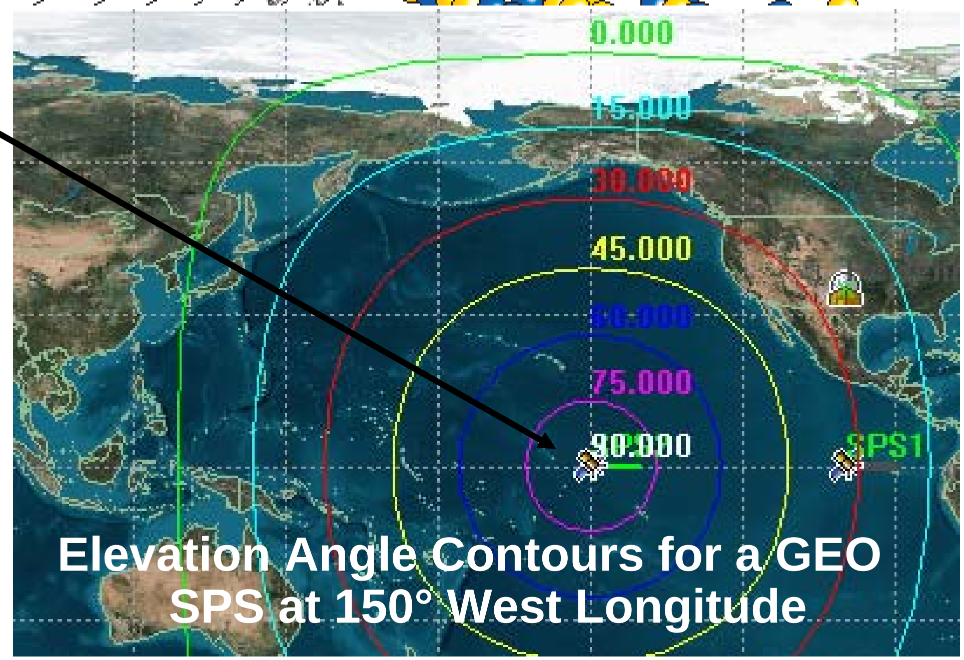
- **Unused GEO orbital slots over the Pacific Ocean**
- **Westernmost GEO satellite shown is at 148° west longitude**
- **An SPS at 150° west longitude can beam power to the west coast of the United States, while maintaining a 2° separation from this satellite**
- **SPS's further west can beam power to Australia and eastern Asia**
- **In the long-term, SSP and communications satellites may share common platforms**





Elevation Angle Contours for a GEO SPS at 150° West Longitude

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Notional Mass of the SSPS System for Forward Military Base (LEO, 5-30 MW)

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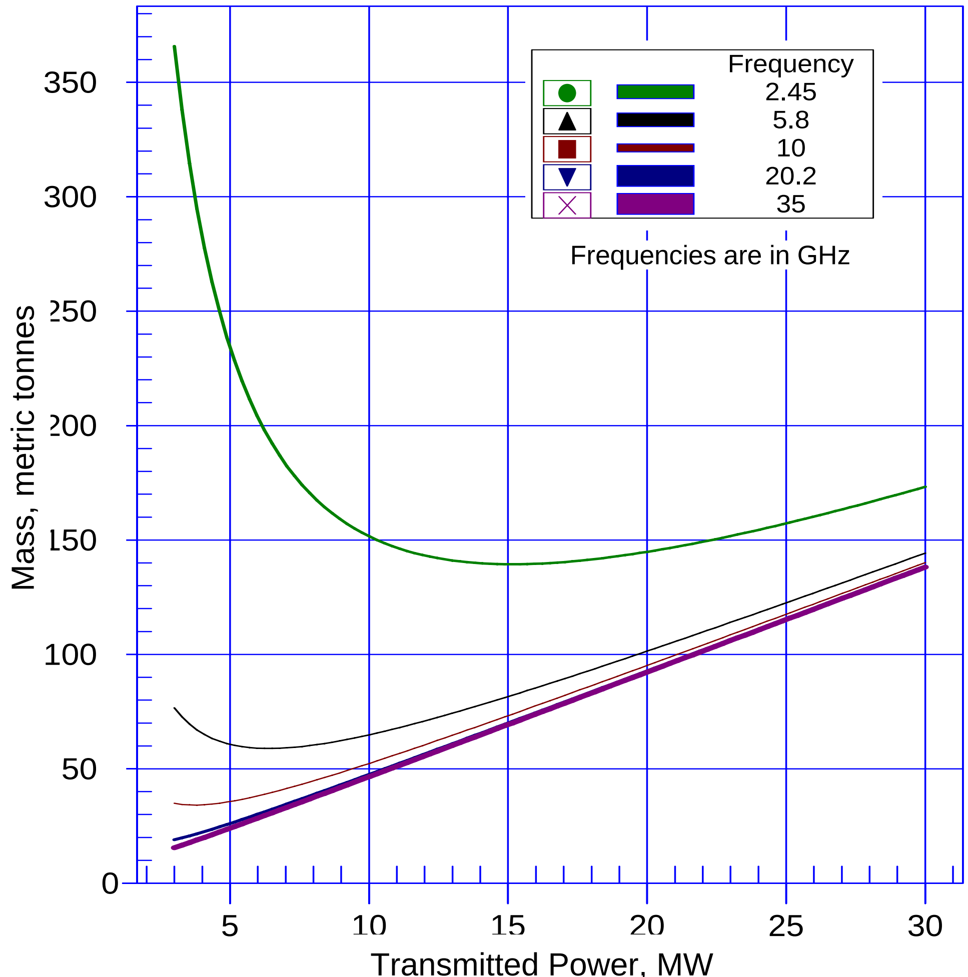

- **First unit cost is for a 10 MW satellite is about $145 per installed watt (including launch but not non-recurring engineering), which is about 2 orders of magnitude higher than that of conventional power plants**
  - Additional units will be somewhat less expensive
  - $100/watt, excluding launch

An SPS using higher microwave frequencies will have a lower mass than one using 2.45 GHz, due to its smaller transmitting antenna size.

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Notional Mass of Geostationary Solar Power Satellites

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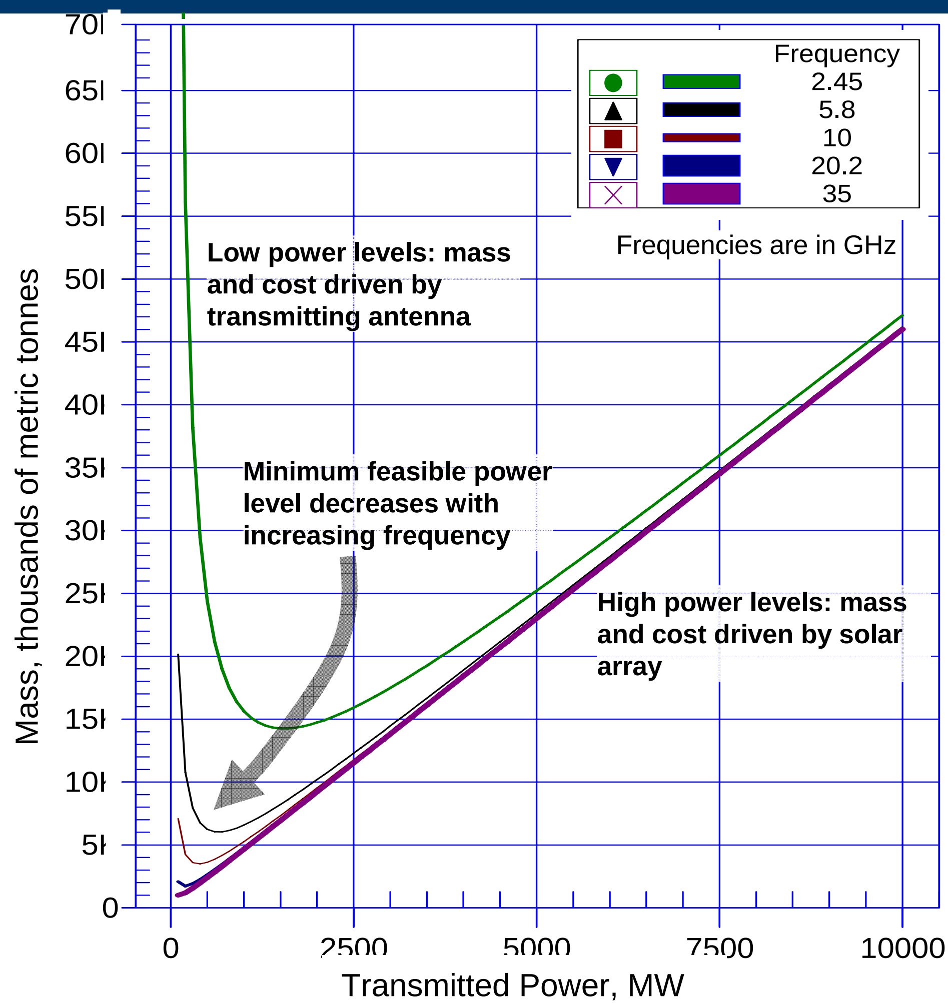

- **For a 5 GW GEO SPS, the installation cost (including launch) is about $240 per watt**
- **Still too high to be competitive with other energy sources for baseload commercial power**
- **System size too large for small niche markets, size could be reduced with laser power transmission**

A single solar power satellite in geostationary orbit can supply several thousand MW of power to the Earth. Many such satellites can supply a significant portion of the world's electricity needs.

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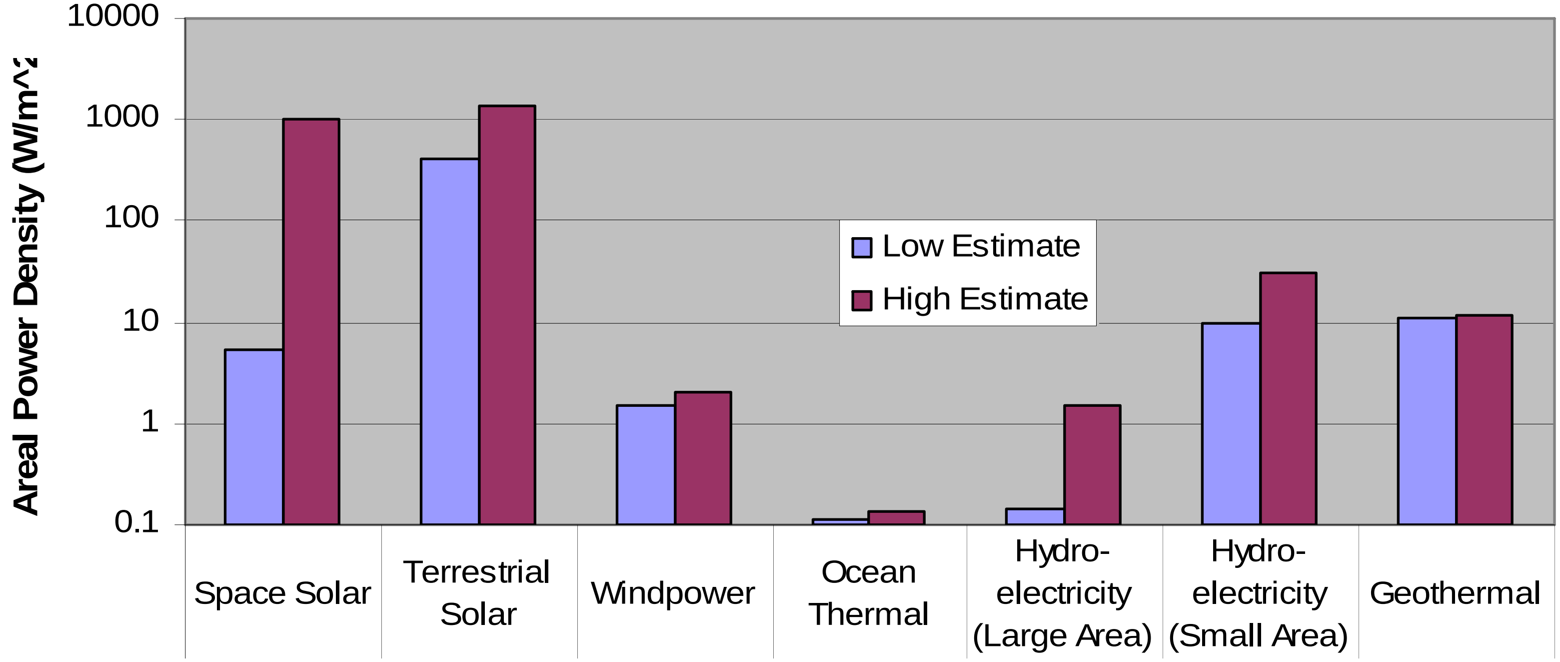
Comparison of Power Per Unit Land Area of Renewable Energy Sources: Before Conversion

- **Naturally-occurring time-averaged power per unit land area at the Earth's surface show that most renewable power sources are very dilute**
  - Chart shows potentially available power per unit area; conversion inefficiencies not accounted for
- **Terrestrial solar power is orders of magnitude better than the others**
  - For SSP, likely range of incident microwave or laser power is shown before receiver array conversion



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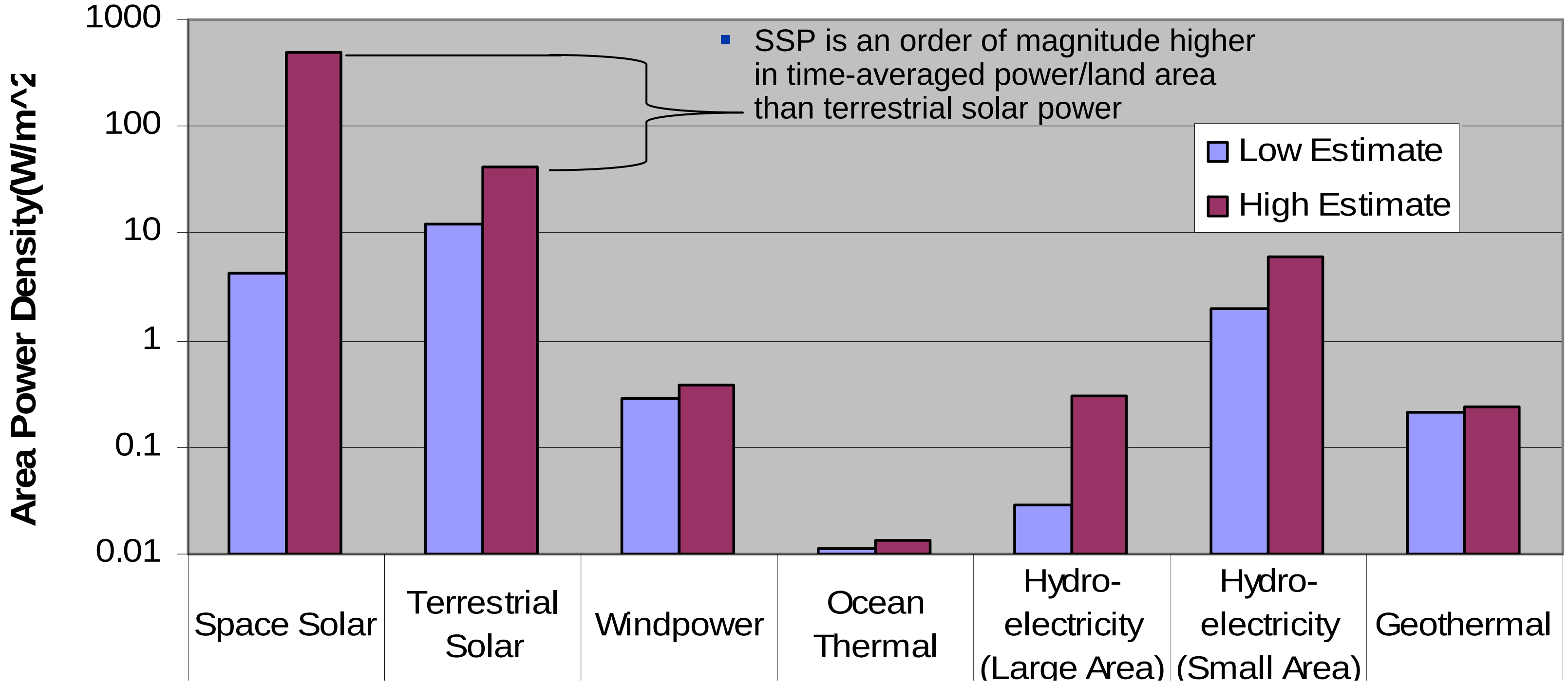
Comparison of Power/Land Area of Renewable Energy Sources: After Conversion

- **When multiplied by achievable efficiencies, the time-averaged power per unit land area of various renewable power sources are as follows:**



SSP delivers higher power per unit land area than other renewables.

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Space Solar Power Advantages

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- **Lower environmental footprint compared to fossil fuels**
- **Lower land use per unit power compared to other renewables**
- **Synergy with other energy sources**
  - Space solar power microwave rectennas can be designed to let light pass through, so the same land area can be used for conventional solar power – or possibly agriculture
  - Solar power satellites using laser power transmission may be able to supply extra illumination to already-existing conventional solar power plants
- **Synergy with space exploration and development**
  - SSP can use resources from space, particularly the Moon
  - Near-term space missions can test and demonstrate SSP technology and prospect for non-terrestrial resources to be used for SSP in a manner consistent with the current plans for Project Constellation
- **SSP may be an economic driver for commercial space development**

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Space Solar Power Challenges

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- **High launch costs**
- **High non-recurring engineering costs**
- **Space industrialization and operations challenges, including low TRL for construction of extremely large structures in space**
- **Earth industrial challenges; e.g., a single 2-GW SPS may require world's entire present annual PV cell production**
- **Microwave beam divergence drives up system size, making graceful growth difficult**
  - Increasing competition for spectrum may also become an issue
- **Laser beams diverge much less, allowing for more flexibility in system size, but have other challenges:**
  - Attenuation by clouds and rain
  - Perception of weapons application
  - Current state-of-the-art efficiencies may be lower than for microwaves
  - Ground-based PV arrays can do "double duty" as laser SSP receivers, but may need to be designed for this at the outset

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A Possible Path to SSP

- **The DoD may wish to reduce the logistics chain to forward military bases by displacing diesel fuel with renewable energy**
- **A first step could be using terrestrial photovoltaics within a base to capture sunlight and partially displace the diesel fuel**
- **Demo-scale SPS's in low Earth orbit can be brought on line and beam power to the PV arrays at night**
- **By use of beam handoffs, the duty cycle of both the space and ground segments can increase as the number of satellites increases**
- **Eventually, the power beaming concept of operations can be simplified by use of geostationary SPS's**

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