Analysis, Modeling, Simulation and Experimentation

Systems Engineering for Space Solar Power Architectures

Martin Bayer, Andrew Born, Dean Davis, David McCormick, Seth Potter
The Boeing Company, El Segundo and Huntington Beach, CA

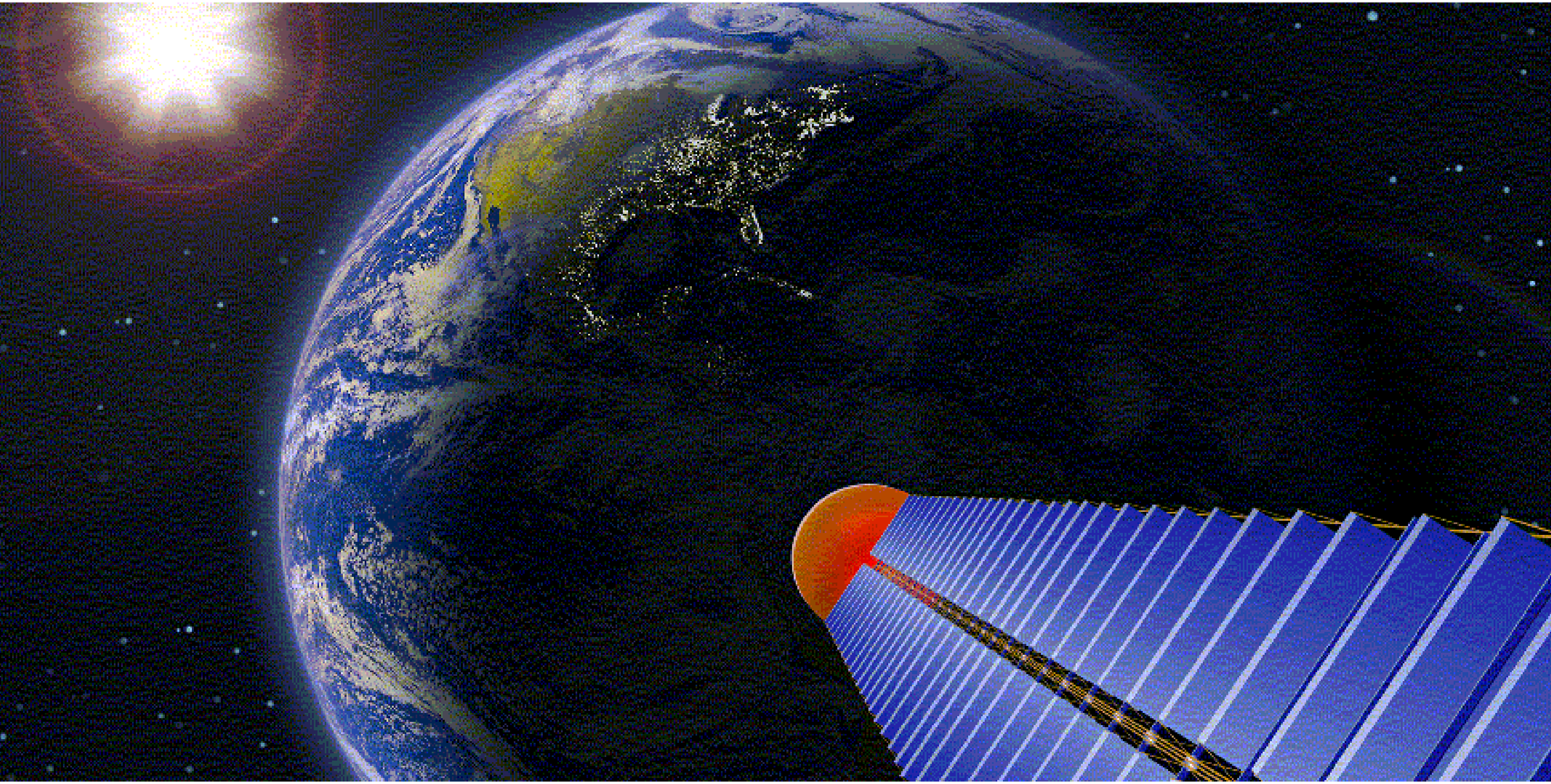
2010 INCOSE Symposium
Chicago, Illinois
12-15 July, 2010

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

Sun Tower Solar Power Satellite

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



The Sun Tower is modular and scalable.

Space Solar Power Advantages

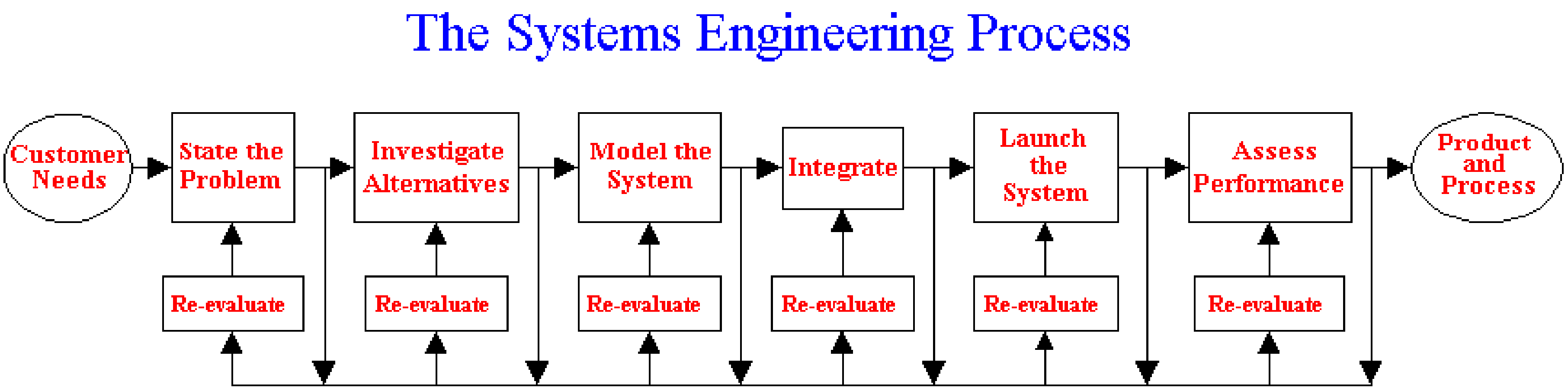
- **Lower environmental footprint compared to fossil fuels**
- **Lower land use per unit power compared to other renewables**
- **Synergy with other energy sources**
  - Space solar power microwave rectennas can be designed to let light pass through, so the same land area can be used for conventional 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**

Space Solar Power Challenges

- **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

Systems Engineering Process Overview

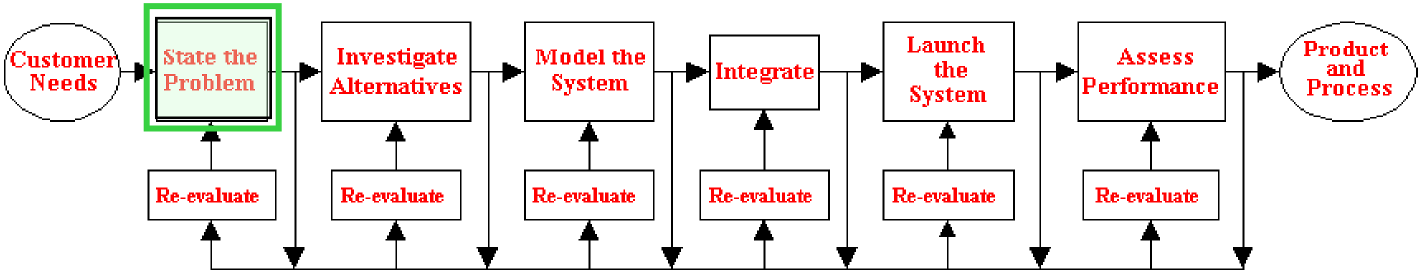
Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



Disciplined process leads to well-focused solutions

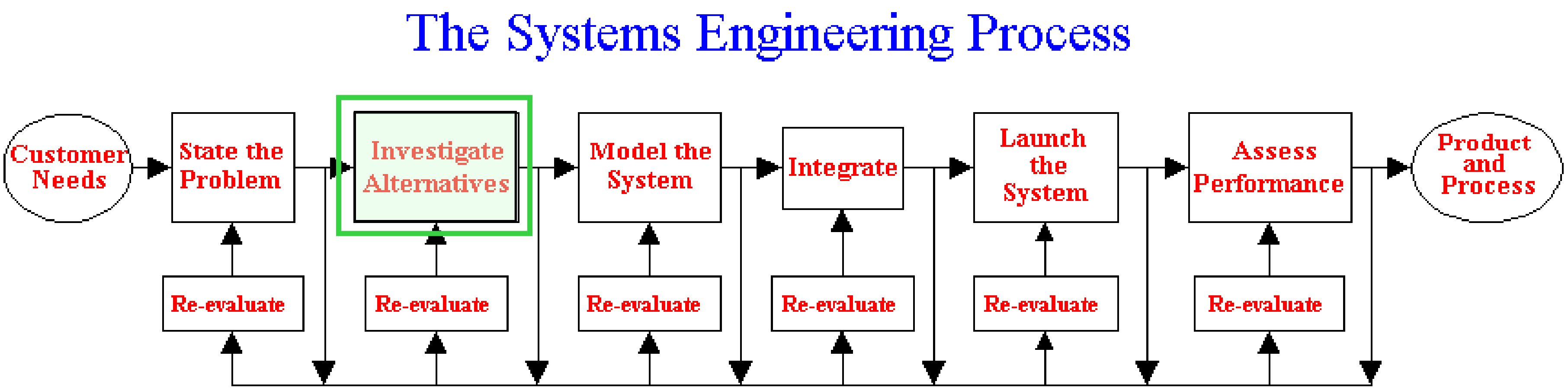
Problem Statement

- **Most existing renewable energy solutions are periodic in their availability**
- **Remote/dangerous locations can extremely high fully-burdened costs of energy**
- **Given Space Solar Power as a potential solution to these, what are the issues with using the technology to:**
  - Generate large-scale power as a utility?
  - Deliver small-scale power to remote locations where competing energy sources are expensive and/or dangerous?



Investigate Alternatives

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



Trade Studies: Assessment Criteria

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

Boeing Trade Studies: Ratings of Options

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**

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

Boeing Trade Studies: Ratings of Options

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**

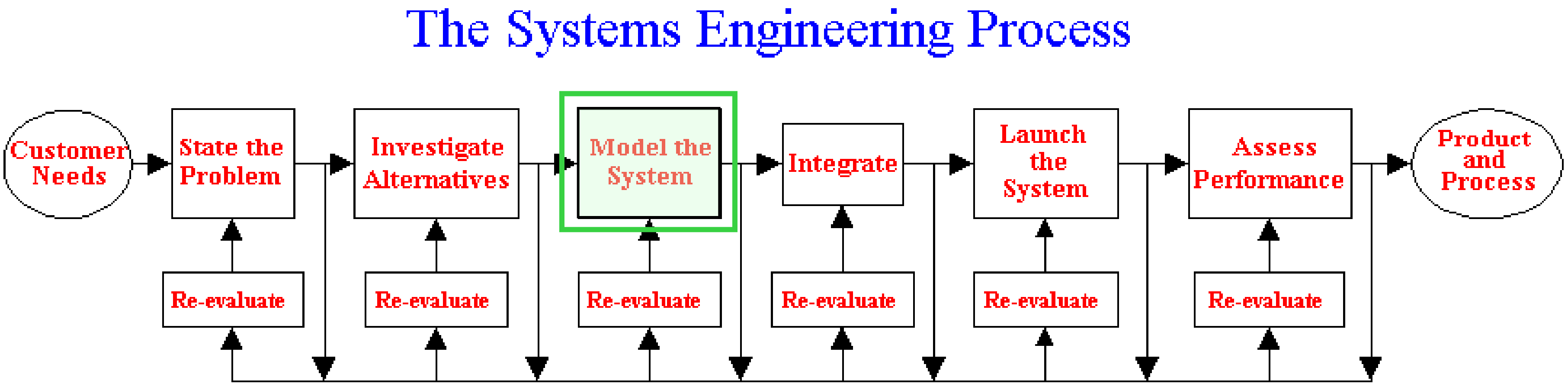
Trade Categories	Trade Options													
Raw Materials Source	Earth	Moon	Near Earth Objects	Phobos/ Deimos										
Manufacturing and Integration Location (may be separate)	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (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**

Initial focus is on major drivers of system design and cost

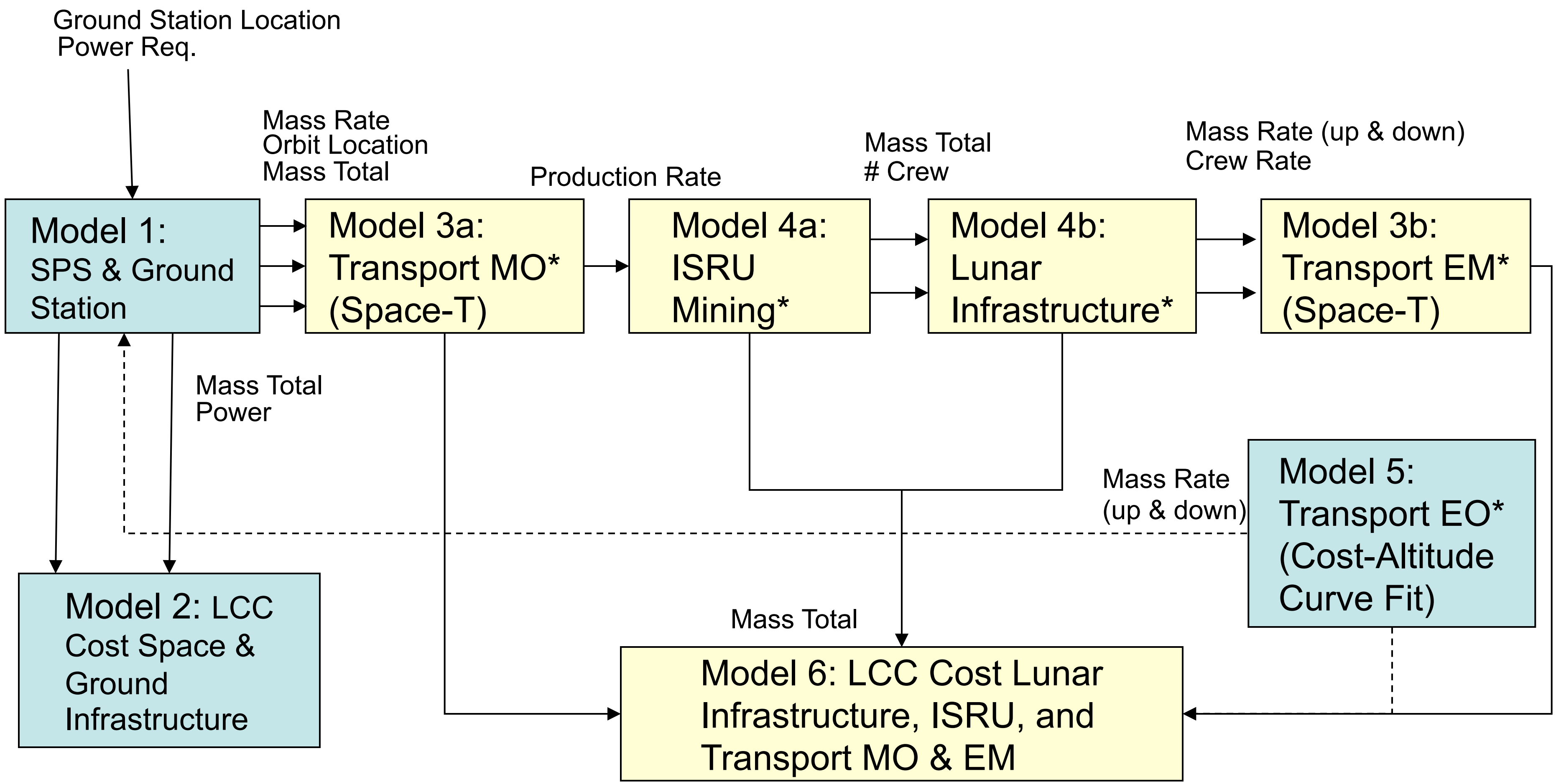
Model the System

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



Model Architecture for Space Solar Power & Lunar Colonization

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



= Colonization domain

= SPS domain

*models are sizing/performance

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

Model 1: Size of Receiver Array

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

where

D_t = diameter of transmitting antenna

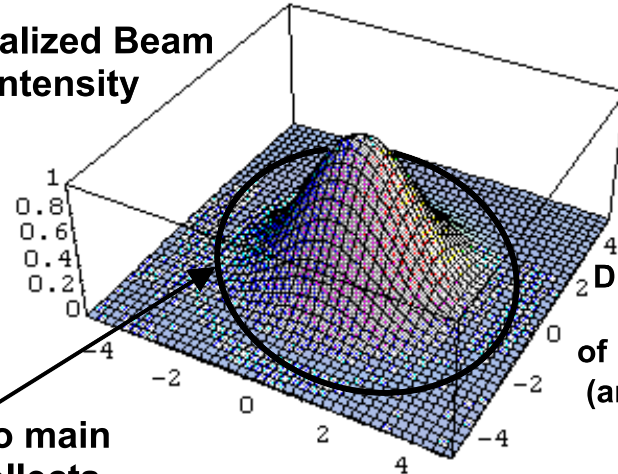
D_r = diameter of receiving antenna

λ = wavelength of beam

x = distance between antennas (determined by orbit)

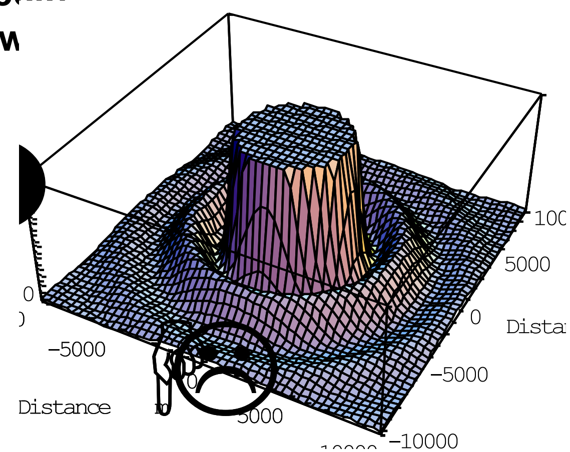
Note : parameters must be in the same units ; e.g., all in meters.

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.

Model 1: Calculation of Beam Intensity

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**

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

where

I_0 = peak beam intensity

P_t = transmitted power

D_t = diameter of transmitting antenna

λ = wavelength

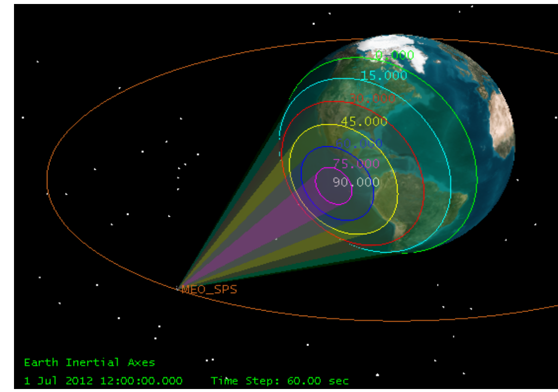
x = distance between antennas

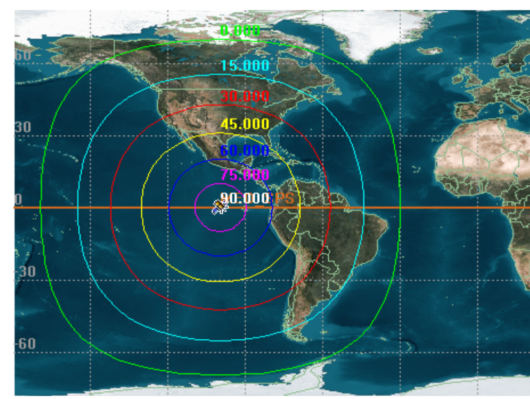
Typically, bean intensity will be a requirement determined by physical and environmental constraints, and the transmitting antenna will be sized to focus the energy to this intensity.

Model 1: Energy Inputs

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**

- **Solar_flux** – W/m2 incident at 1 AU in space
- **Transmitting_Period** – Time between beaming events
- **Storage_Power_Constant** – W/kg output of the on-orbit storage medium
- **Eff_SolarCell** – Energy efficiency of the solar cells
- **Eff_Storing** – Energy efficiency of on-orbit storage
- **Eff_StorageOutput** – Energy efficiency of on-orbit storage discharge
- **Eff_Storing_onGround** – Energy efficiency of ground storage
- **Eff_StorageOutput_onGround** – Energy efficiency of ground storage discharge
- **Eff_Transmitting** – Power efficiency of the transmitter
- **Eff_receiving** – Power efficiency of the rectenna
- **fraction_visible –** fraction of the Transmitting period that the SSPS is beaming power
- **fraction_storing –** fraction of the non-beaming period that the SSPS is storing power on-orbit
- **fraction_covered** – fraction of the beam patch that the rectenna covers
- **SP_unit_wt** – kg/m2 of the solar panel
- **Storage_unit_wt** – kg/Wh of the on-orbit storage
- **Transmitter_unit_wt** – kg/m2 of the transmitter
- **Bus_wt_factor** – factor applied to the above to get the remainder of the satellite





Model 2: Cost Model Process Flow Overview

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.

Model 2: Notional SSP Cost Modeling Assumptions

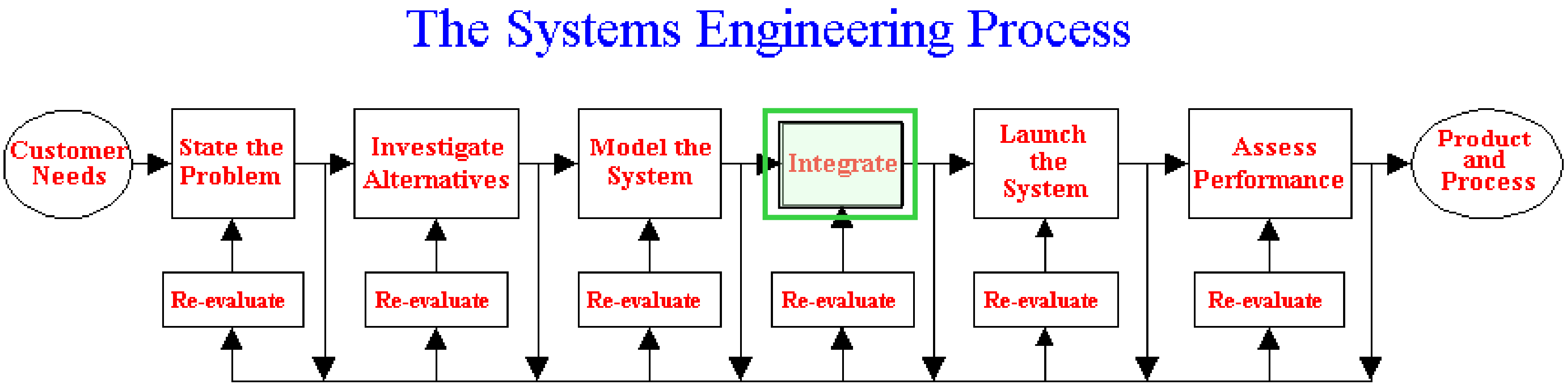
- Level 0 Analysis
- Constant year dollars 2008
- Technology assumed to be mature to 2028
- 97% learning curve for production
- 30 Year mean mission duration (MMD) for each satellite
- Mass in kg
- Estimate includes Spacecraft, Rectenna, Systems Engineering (SE), Program Management (PM), Assembly Integration &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

Model 5: Earth-to-Orbit Transportation

- **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

Integrate / Exercise the Models



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.*

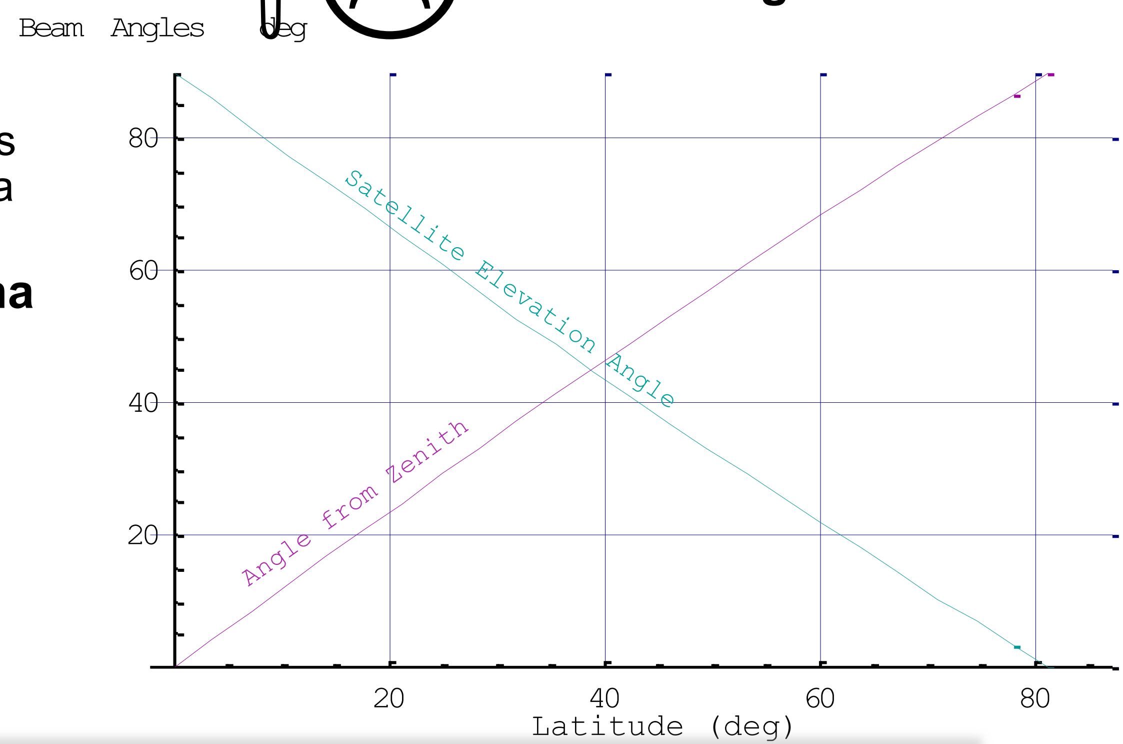
- Discussions at the NSSO SBSP meeting in 9/07 emphasized power levels of 5-15 MW at forward military bases having available land parcels of ~1000 meters in width to support a rectenna array

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

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.

SSP May Have Near-Term Utility for Military Bases

- **Much of the cost in lives and dollars of operating a military base in a war environment is due to the delivery of fuel**
- **Cost of delivery of gasoline under such circumstances is about \$100/gallon, which contains 130 megajoules of energy = 36 kWh**
- **At this rate, 40 remote military bases (each using 5 MW) will require 40 bases x 5 MW/base x 24 hours/day x 30 days/month = 144,000 MWh/month**
- **This is equivalent to 4,000,000 gallons of fuel per month or \$400 million per month for fuel.**
  - Conversion from thermal to electrical energy not accounted for. Actual fuel usage will be higher.
- **These bases, using a total of 200 MW could instead be supplied by just 20% of the power beamed from a single 1 GW power satellite**
- **Graceful growth toward this market may be achievable by considering a constellation of smaller (5 to 10 MW) satellites.**

SSP can be competitive with other energy sources in highly stressed environments.

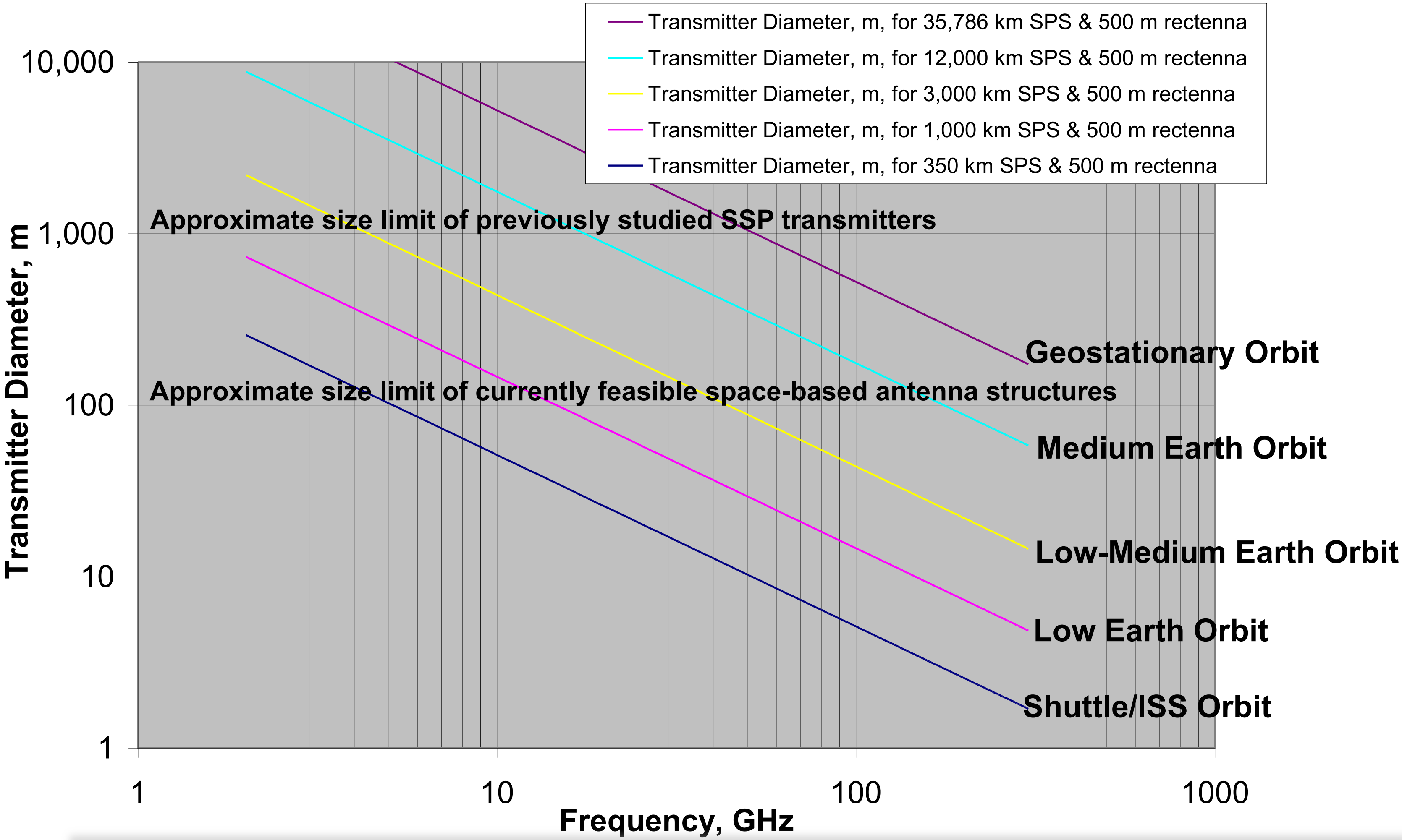
Military Mission Needs: Feasibility

- **Will the beam fit into the ground site as it spreads out?**
- **Forward military bases will probably have no more than about 1000-meter-wide parcels of land to receive the beam**
- **Focusing it more narrowly may need a huge antenna, and may make the beam too intense**
- **Our study looked at a range of options to see if this is feasible**
- **With an appropriate choice of frequency and orbit, it can work**

SSP ground segment requirements are compatible with military base capabilities.

Near-Term Market: Military Bases

Case 1: 500-meter rectenna – can receive up to 10 MW at power densities comparable to earlier studies (~22 mW/cm^2 peak)

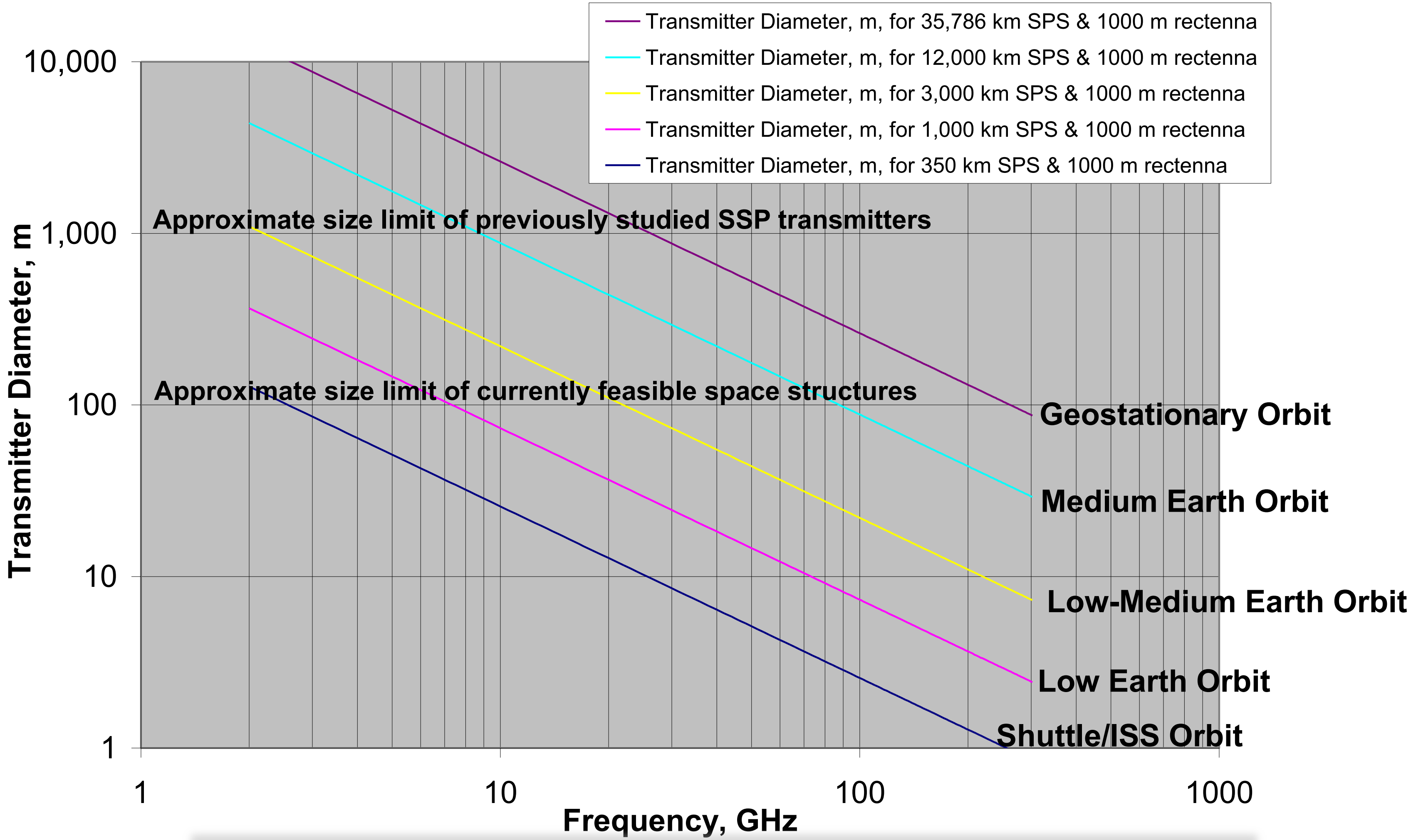


Transmitting antennas for low frequencies must be extremely large to focus power into a military base.

Near-Term Market: Military Bases

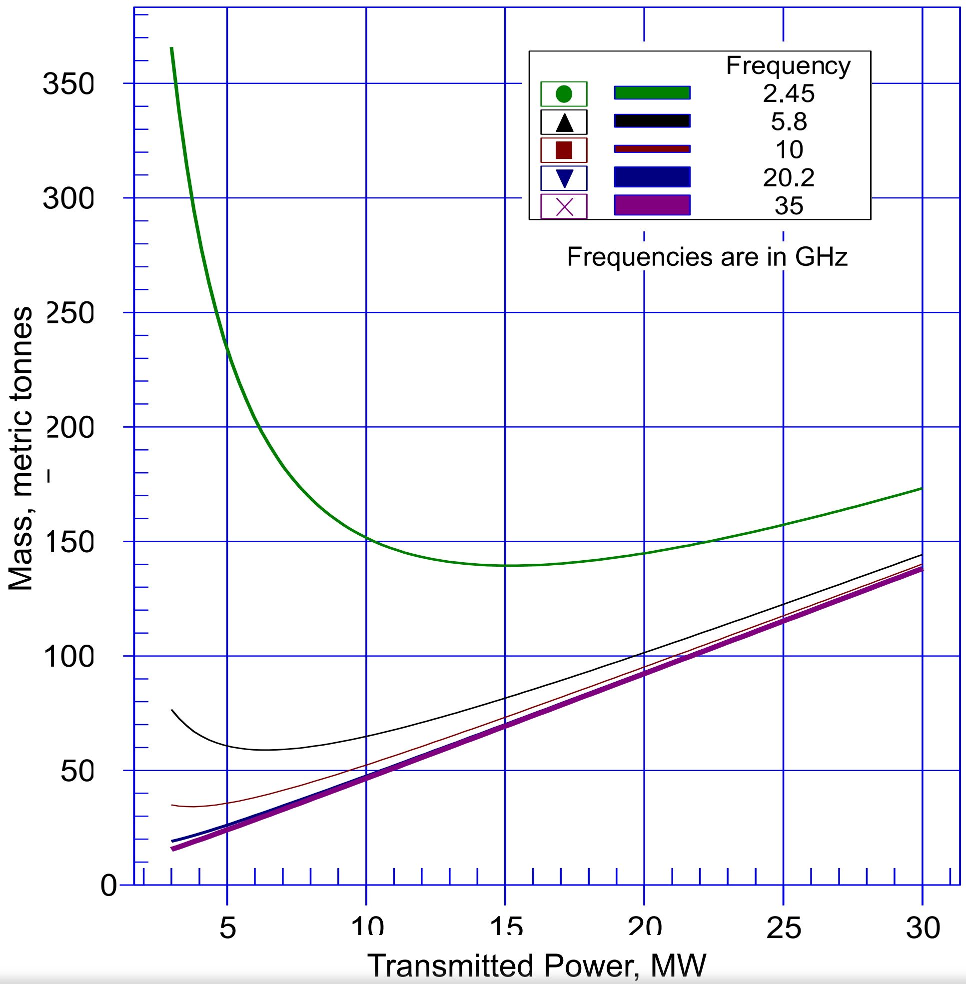
Case 2: 1000-meter rectenna – can receive up to 40 MW at power densities comparable to earlier studies (~22 mW/cm^2 peak)

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



If more land is available for a rectenna, a somewhat smaller transmitting antenna will be needed and more power can be received.

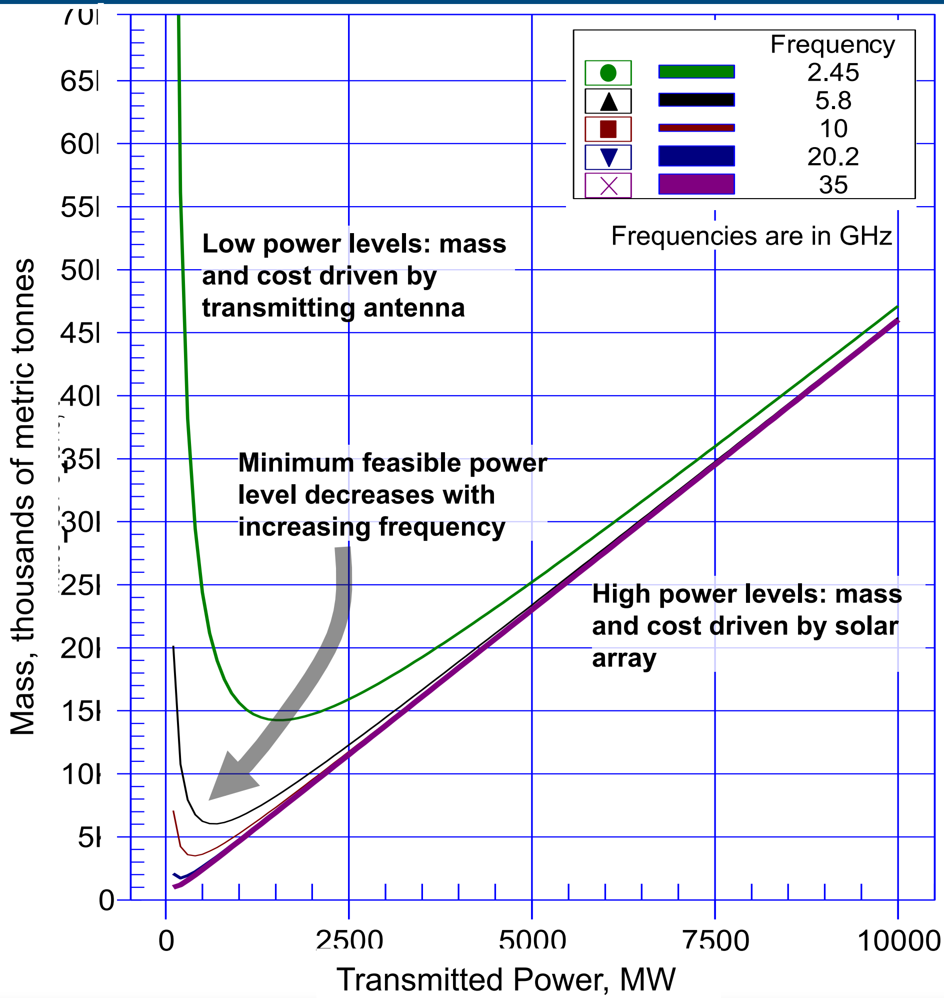
SSPS System for Forward Military Base (LEO, 5-30 MW)



- **Low Earth orbit solar power satellites will be used most effectively if there are several satellites serving several ground stations**
- **With beam handoffs, each satellite and ground station can be used for many hours each day**

An SPS using higher microwave frequencies will have a lower mass than one using 2.45 GHz, because the transmitting antenna will be proportionately smaller.

Geostationary Solar Power Satellites



- **A geostationary satellite can beam power to a ground station continuously, but with today's launch systems, the cost will still be too high to be competitive with other energy sources for baseload commercial power**
- **System size is 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.

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- **Do at least one of the following three things:**
  1. Decrease the wavelength
     - Power transmission efficiency may decrease
     - Weather outages may increase
  2. Lower the orbit
     - Dwell times over ground site get shorter, so need more satellites or energy storage
  3. Leave heavier components on the ground
     - Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system
- **There are at least two ways to accomplish #3:**

3a. Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector

3b. Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- **Do at least one of the following three things:**

1. **Decrease the wavelength**
   - **Power transmission efficiency may decrease**
   - **Weather outages may increase**
2. Lower the orbit
   - Dwell times over ground site get shorter, so need more satellites or energy storage
3. Leave heavier components on the ground
   - Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system

- **There are at least two ways to accomplish #3:**

3a. Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector

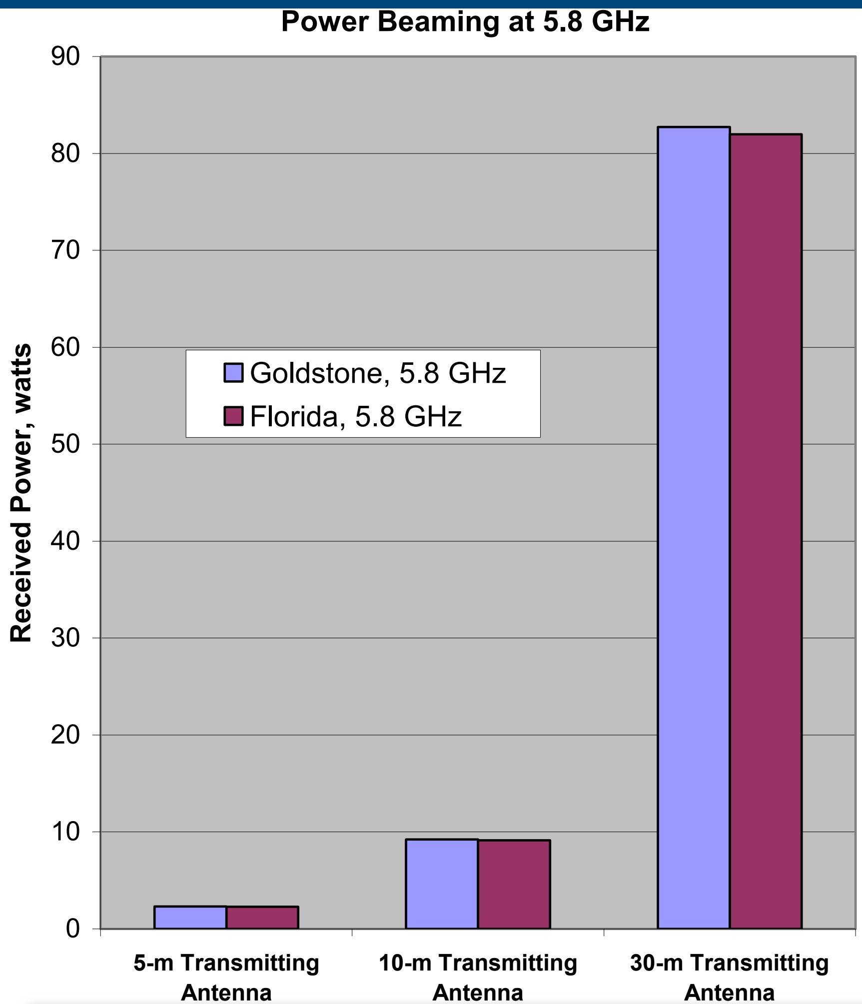
3b. Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector

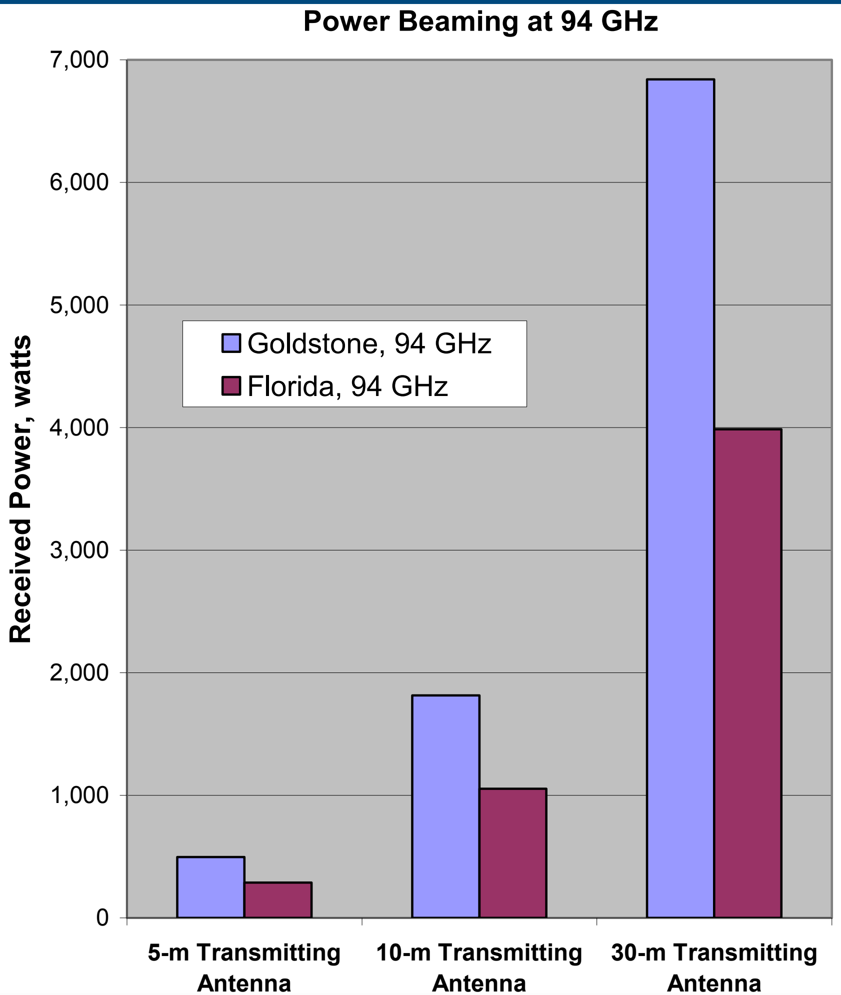
Power Beaming Demo: Wavelength Trade Study

- **Frequency = 5.8 GHz and 94 GHz**
- **Beaming distance = 350 km (e.g., ISS directly overhead)**
- **Total power transmitted = 10 kW**
- **Transmitting antenna diameters = 5 meters, 10 meters, 30 meters**
- **Receiving locations**
  - Goldstone, CA
    - Atmosphere: dry
    - Receiver altitude: 970 meters
    - Receiving antenna diameter: 70 meters
  - Florida
    - Atmosphere: cloudy
    - Receiver altitude: sea level
    - Receiving antenna diameter: assume 70 meters for consistent comparison

The Boeing-funded trade study considered two very different receiving station environments.

Summary of Boeing Demo Study Results: 10 kW Transmitted from ISS to Ground





At 94 GHz, much more power can be focused on the 70-m receiver than at 5.8 GHz. However, 94 GHz is significantly attenuated by clouds.

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- **Do at least one of the following three things:**

1. Decrease the wavelength
   - Power transmission efficiency may decrease
   - Weather outages may increase
2. **Lower the orbit**
   - **Dwell times over ground site get shorter, so need more satellites or energy storage**
3. Leave heavier components on the ground
   - Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system

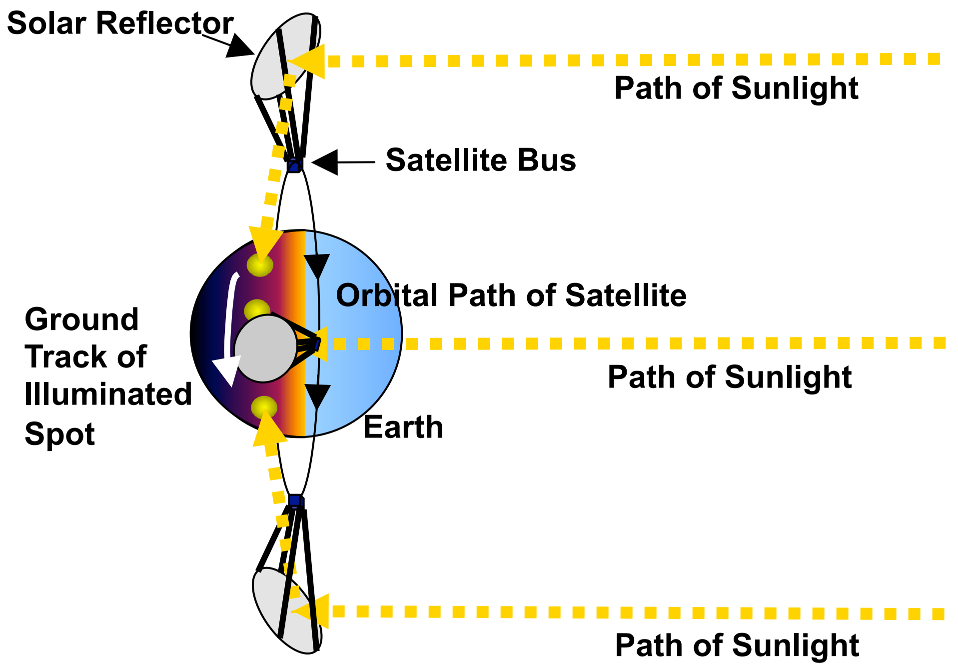
- **There are at least two ways to accomplish #3:**

3a. Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector

3b. Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector

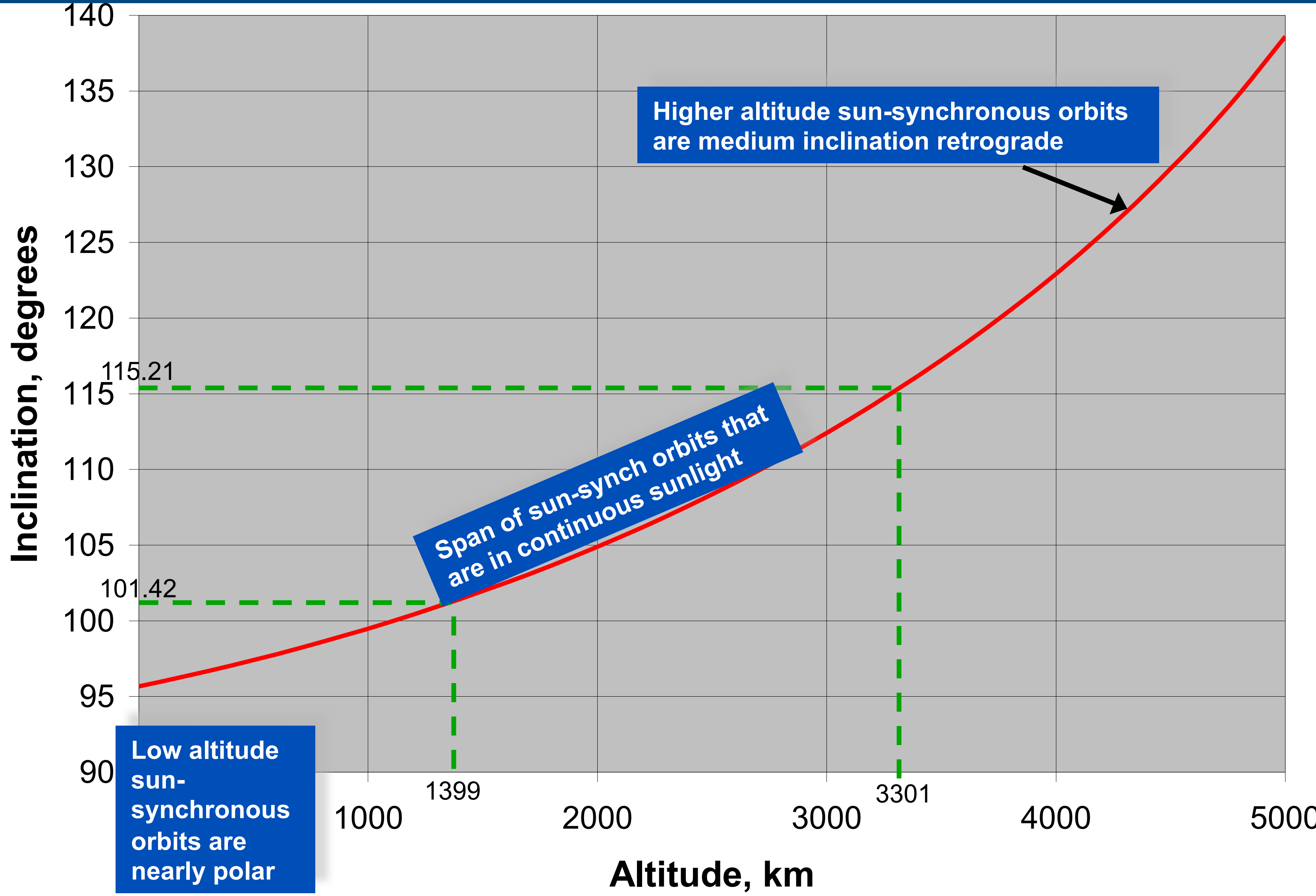
Sun Synchronous Orbits

- **A satellite in a sun-synchronous orbit around the line separating Earth's day and night sides will nearly always be in sunlight and will require only minimal steering**
- **Low orbit**
  – Nearly polar
  – Reflector size relatively small
  – However, may not be able to reach deep into the night side of the Earth
- **High LEO / Low MEO**
  – Somewhat off polar, so could be in Earth's shadow during part of each orbit around the solstices
  – Could reach deeper into Earth's night side
  – Reflector size is larger
  – At higher altitudes, sun-synchronicity may not be achievable

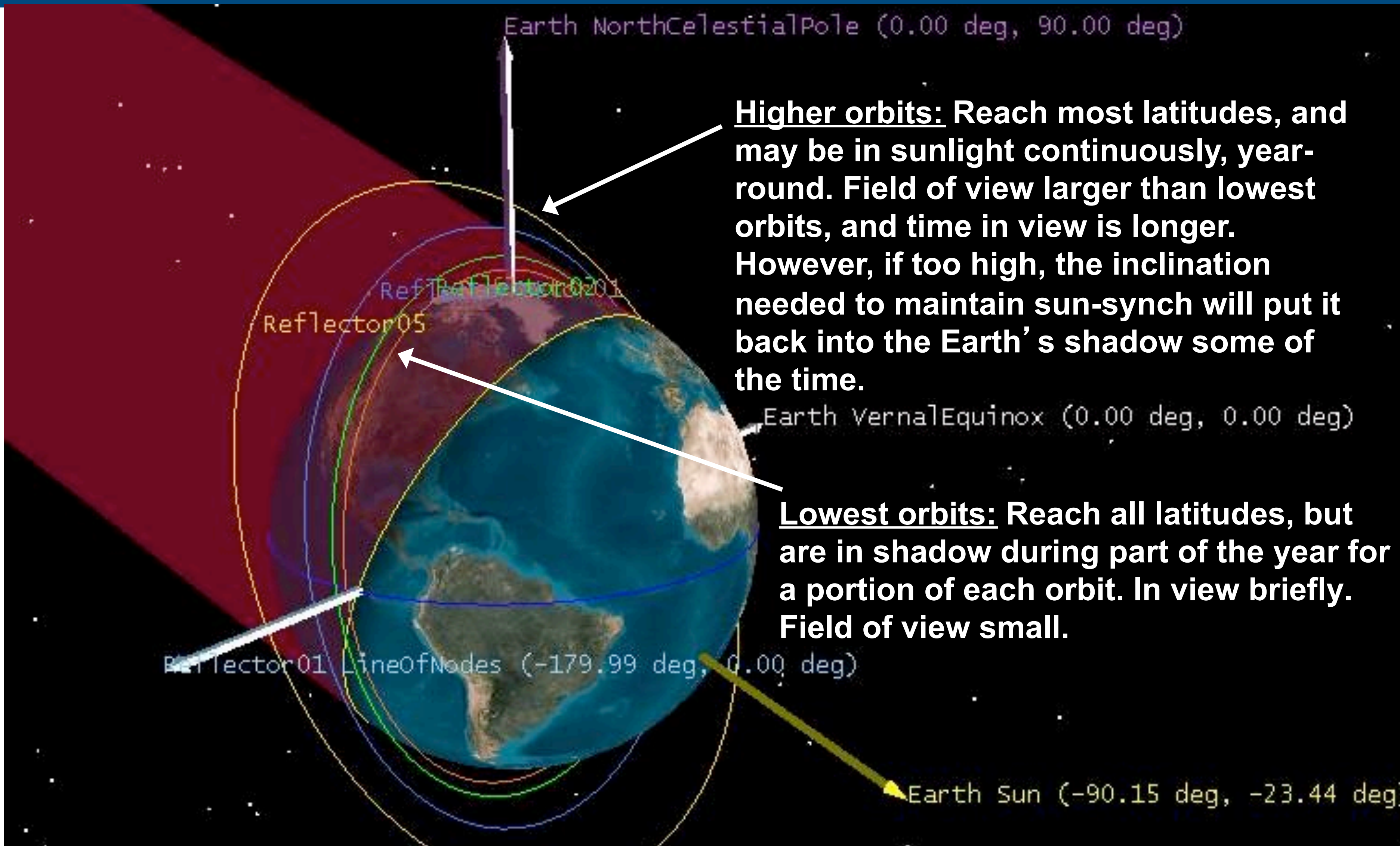


Circular Sun-Synchronous Orbits: Inclination Depends on Altitude

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



Sun-Synchronous Orbit Altitude: Too High or Too Low Will Cause Shadowing



Higher orbits: Reach most latitudes, and may be in sunlight continuously, year-round. Field of view larger than lowest orbits, and time in view is longer. However, if too high, the inclination needed to maintain sun-synch will put it back into the Earth's shadow some of the time.

Lowest orbits: Reach all latitudes, but are in shadow during part of the year for a portion of each orbit. In view briefly. Field of view small.

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- Do at least one of the following three things:

1. Decrease the wavelength
   - Power transmission efficiency may decrease
   - Weather outages may increase
2. Lower the orbit
   - Dwell times over ground site get shorter, so need more satellites or energy storage
3. **Leave heavier components on the ground**
   - **Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system**

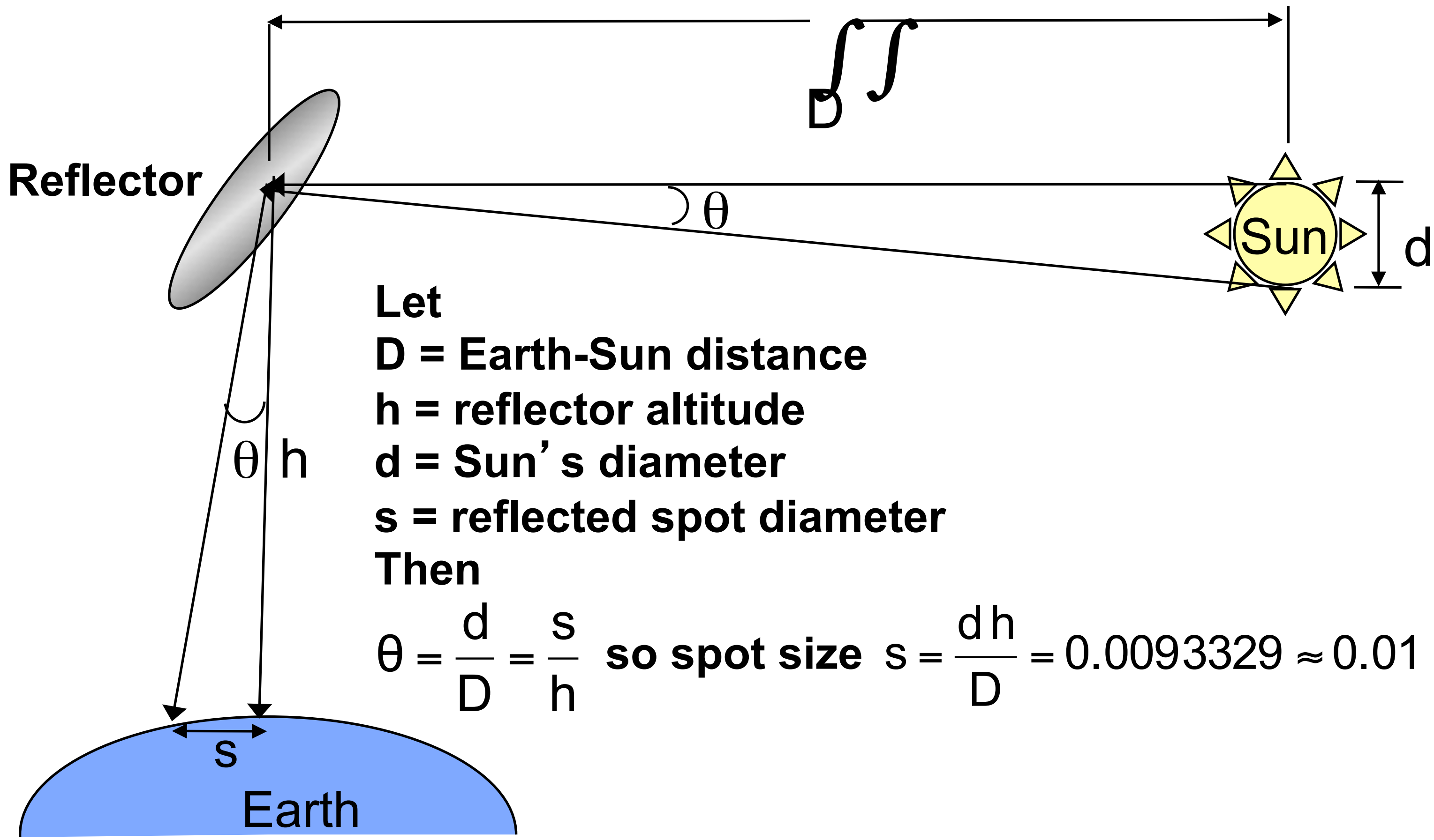
- **There are at least two ways to accomplish #3:**

3a. **Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector**

3b. **Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector**

Solar Reflector Geometry

Advanced Systems | **Analysis, Modeling, Simulation and Experimentation**



Let

D = Earth-Sun distance

h = reflector altitude

d = Sun's diameter

s = reflected spot diameter

Then

$\theta = \frac{d}{D} = \frac{s}{h}$ **so spot size** $s = \frac{dh}{D} = 0.0093329 \approx 0.01$ radian

Spot size is independent of reflector size. Reflector size does, however, determine spot brightness.

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- Do at least one of the following three things:

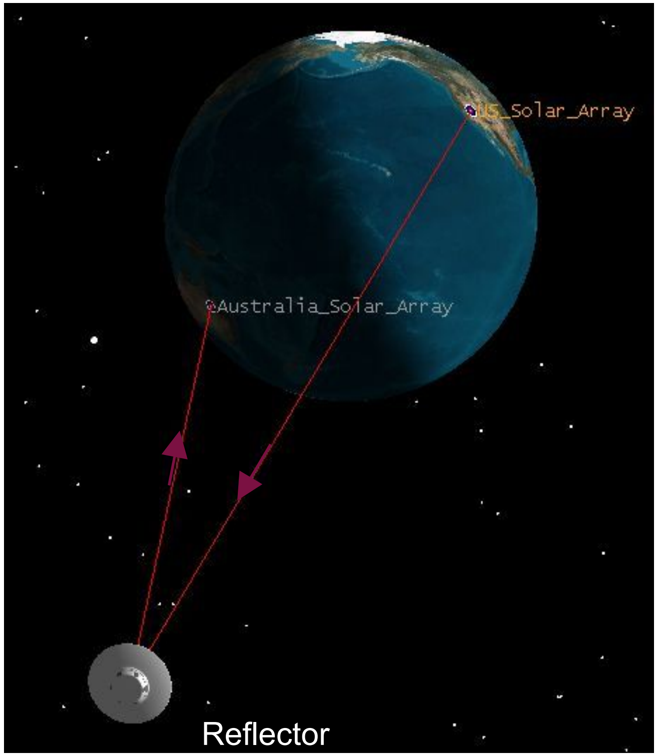
1. Decrease the wavelength
   - Power transmission efficiency may decrease
   - Weather outages may increase
2. Lower the orbit
   - Dwell times over ground site get shorter, so need more satellites or energy storage
3. **Leave heavier components on the ground**
   - **Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system**

- **There are at least two ways to accomplish #3:**

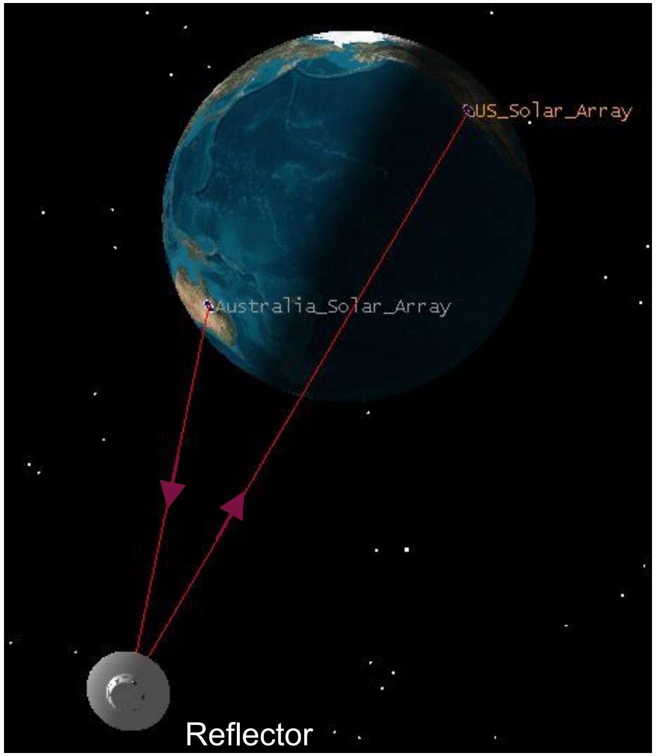
3a. **Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector**

3b. Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector

Orbital Reflectors Can Enable Growth Toward a Global Power Grid



During daylight hours, a photovoltaic array in the US powers the local grid and places excess power into a laser which is relayed to an array in Australia.



If the array in Australia also has a laser, then twelve hours later, the process can be reversed.

An orbiting reflector can send beamed power around the world, so that solar arrays can be used at night.

How to Make the SSP Satellite Smaller (In space, we usually mean lighter)

- Do at least one of the following three things:
  1. Decrease the wavelength
     - Power transmission efficiency may decrease
     - Weather outages may increase
  2. Lower the orbit
     - Dwell times over ground site get shorter, so need more satellites or energy storage
  3. **Leave heavier components on the ground**
     - **Much of the mass of a solar power satellite consists of the power transmission apparatus and the power management and distribution (PMAD) system**
- **There are at least two ways to accomplish #3:**

3a. Generate power using a solar collector on the day side of the Earth and relay power to a solar array on the night side with an orbiting reflector

3b. **Redirect sunlight to a solar array on the night side of the Earth using an orbiting reflector**

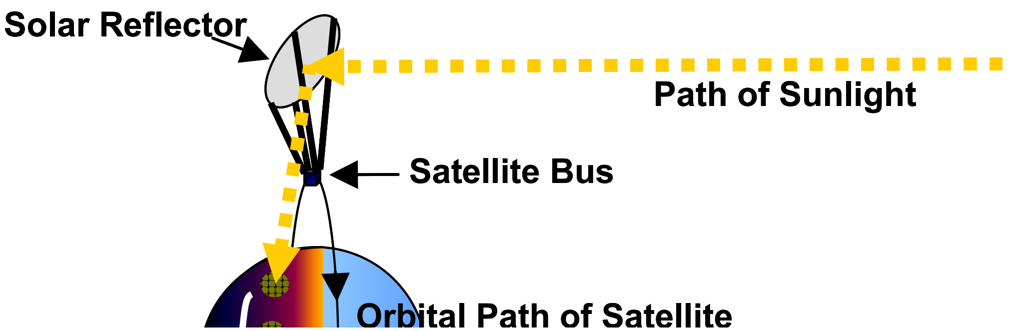
Questions that Drive Reflector System Design

- **How large should a solar reflector be?**
  - For reflected sunlight, size is determined by altitude (higher means larger for equivalent brightness) and desired spot brightness (brighter means larger for a given altitude)
- **How many reflectors are required for continuous power?**
  - Only one, if in equatorial GEO, but reflector (or set of reflectors aimed at a common ground area) will be huge
  - For lower orbits, depends on time each one is in view, which is determined by altitude
- **What orbit should the reflector be in?**
  - GEO: simplest architecture, but satellite will be huge
  - Very low Earth orbit ("LEO", like Space Shuttle or International Space Station): satellites small, but need lots of them to get continuous power
  - Somewhat higher LEO, such as the sun-synchronous orbits mentioned earlier: may be an effective compromise

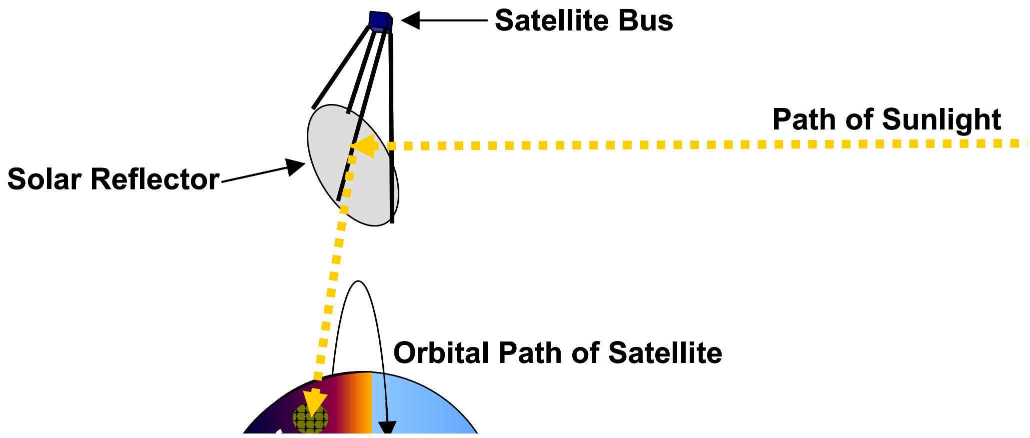
Possible Configurations for Solar Reflector Example 1: Sun-Synchronous Gravity Gradient

- **Satellite is in near-polar sun-synchronous orbit – can be oriented to orbit around the Earth's day/night division**
- **Gravity gradient stabilized**
- **Orientation of reflector fixed over the course of a day, but will have to be slowly steered seasonably**
  - Can be steered by adjusting tension on wires or length of "spokes"
- **Two configuration options – choice depends on distribution of mass**

Example 1a: Bus hangs below reflector, as seen earlier

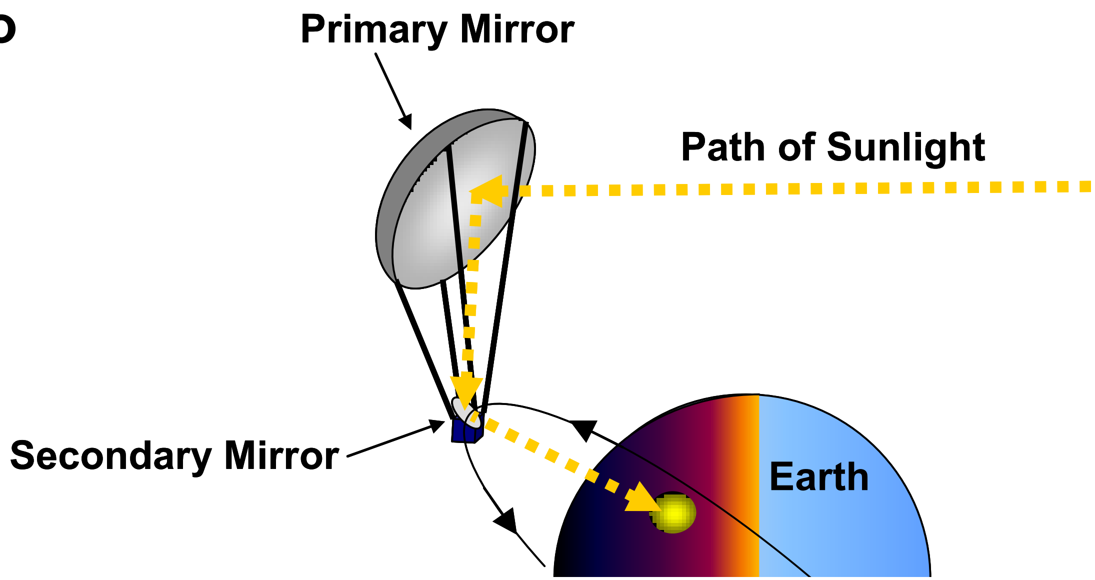


Example 1b: Reflector hangs below bus



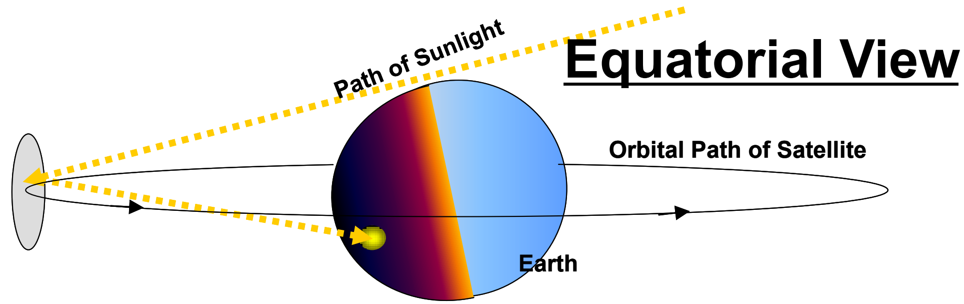
Possible Configurations for Solar Reflector Example 2: Two-Mirror Concept

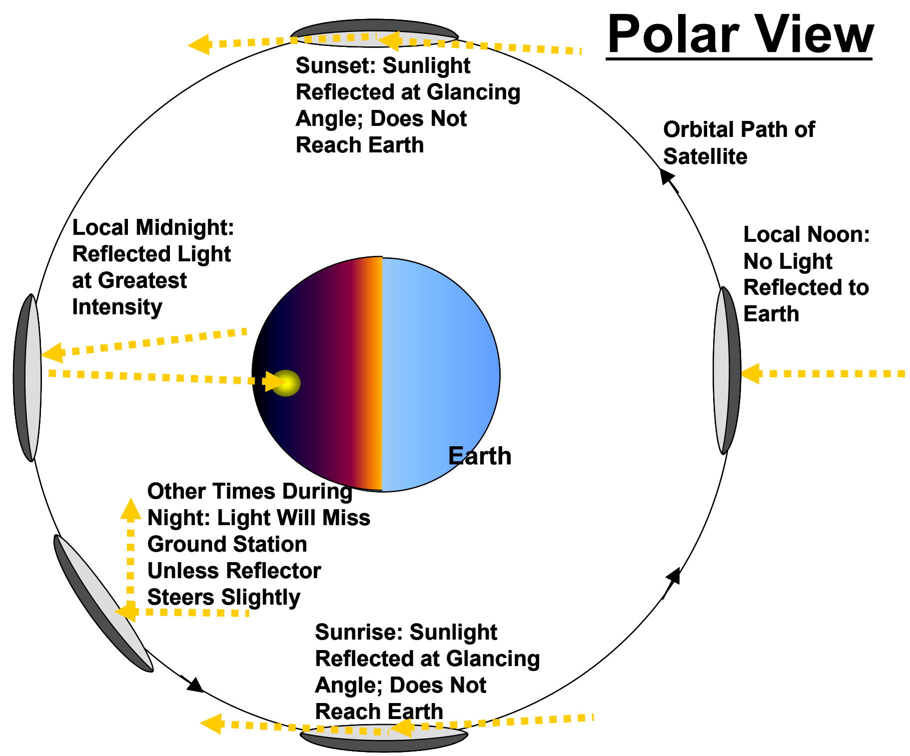
- **Primary mirror tracks sun**
  - May be parabolic to concentrate light onto secondary mirror
- **Secondary mirror steers to track ground station**
- **May be useful for inclined orbits and/or low orbits, where rapid steering is necessary**



Possible Configurations for Solar Reflector Example 3: Geostationary Perpendicular to Orbital Plane

- Satellite is a simple monolithic structure that orbits roughly perpendicular to the orbital plane
- Provides power to the ground at night
- Must be slightly off-perpendicular by an amount that depends on time of year and location of ground station – some north-south steering is necessary
- Some east-west steering necessary during the night part of each orbit to maintain illumination incident on ground station





Conclusions

- **Near-term use of SSP technology can provide risk burn-down, as well as practical utility**
- **Mass to be deployed on orbit for early initial operating condition can be minimized by judicious choice of power transmission wavelength, orbit, and system architecture**
- **Reflector demos may be functionally and structurally traceable to orbiting solar reflectors, orbiting (laser) power relays, and reflector concentrator SPSs**
- **These can form the backbone of a network-centric power-on-demand system**

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 or at forward locations replacing disposable battery portage**
- **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**