Mirror Satellites for Solar Power from Space

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Outline

• Space Power Satellite Prior Art Designs
• Alternate SPS Design - Space Mirrors in Dawn Dusk Polar Orbit
• Common Requirement– Space Mirrors
• Prior Art Space Mirror Designs
• Proposed Mirror Satellite Design
• Conclusions
Space Power Beaming Prior Art Concept – Very Complex

1999-2000: One Product of the SERT Program

Integrated Symmetrical Concentrator Concept

Incident Sun Light in GeoStationary Earth Orbit @ 1358 W/m²

Photovoltaic (PV) Conversion @ 35-50% Efficiency and ~1000 W/kg

Phased Array Conversion to Microwave RF Beam @ 2.45 GHz or 5.8 GHz and >80% Efficiency Goal

Wireless Power Transmission from Space to Earth @ ~90% Efficiency Goal

Rectifying Antenna Conversion of RF to Voltage @ >85% Efficiency Goal

Management & Distribution of Baseload Power to Local Grid (e.g., 1.2-4.8 GW, 1-10 Beams)

High Power Density Microwave Beam

Overall Dimensions: ~5 km x ~15 km

Large Thin-Film Optics

Typical Scenario
Large SPS in GEO (e.g., 24 Satellites & ~30 GW Total)
Microwave Power Transmission (2.45 GHz or 5.8 GHz)
Power ~ 1.2 GW (Delivered on the Ground)

6.5 km x 8.5 km Rectifying Antenna (Rectenna at 5.8 GHz)

Multi-Bandgap PV

Solid State WPT

Low Power Density Microwave Beam

June 2003

SSP_14
Power Soletta proposed by Dr. Ehricke
(Prior Art Concept 1978)

1.) 4200 km orbit
2.) Sun’s disc size is 10 mrad
   42 km diameter spot on earth
3.) 180 GW power station

Mirrors in space beaming sunlight
to earth is simpler than converting
it to electricity and then microwave
beaming it down and converting it
back again to electricity.

<table>
<thead>
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<td>1.) 4200 km orbit</td>
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<td>2.) Sun’s disc size is 10 mrad</td>
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<td>3.) 180 GW power station</td>
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Recent NASA ALPHA-SPS Design Uses Thousands of Self Deploying Mirrors with Pointing Capability
Alternate SPS Design – Space Mirrors in Sun Synchronous Dawn Dusk Polar Orbit

SPS DREAM
Sunlight for 24 hrs per day and solar electricity at very low cost.

Sorry, sunlight for 14 hrs per day but, yes, at very low cost.

How?? Listen!

Crazy Idea

Sunlight

Earth
N
Revolutionary Concept:

Lightweight mirrors in a Dawn-Dusk Orbit beam sunlight to earth PV stations providing solar electricity in evening & winter for 14 hours per day increasing solar power station capacity factor to 60% & reducing Solar electricity cost to Under 6 cents / kWh.
Large Terrestrial Solar Fields are being installed but electric power production in evenings & winter is desirable:

Photographs of multi MW solar PV power fields in India, California and Germany.
Concentrated Solar Power Fields are also potential Targets for more solar electricity in the early morning and Evening producing lower cost electricity.

Photographs of 100 MW CSP field in Abu Dhabi In 2013
Spy Satellite Images from Film “Patriot Games”
Proposed Mirror Satellite Constellation

This 18 evenly spaced mirror satellite constellation is 1000 km high in a sun synchronous orbit around earth with a 30 degree latitude and longitude view. 30 degree longitude equals 2 hours.

N is up. The circle represents the earth’s surface at 36° latitude. As the world turns, the target ground station moves up and the slant angle and slant range increase. 15° represents 1 hour. When the slant angle is 48°, the earth has turned 15° or 60 min.

The mirror satellites can be pointed using CMGs as on the International Space Station. Here, the mirror satellites are very simplified and exaggerated in size simply to illustrate a concept.
Revenue Projections and Cost for Mirror Satellite Constellations

Assumptions – 2022 - Revenue
1.) 18 satellites in dawn/dusk orbit 1000 km above earth.
2.) The sun’s disc diameter viewed from earth is 10 mrad. This implies solar spot size on earth from a mirror up 1000 km equal 1000 tan(10 mrad) = 10 km.
3.) Assume each mirror satellite array has diameter of 10 km.
4.) Now assume that in the year 2022 there are 40 ground stations distributed around the world that the 18 satellite constellation will serve and that the constellation gives 1 hr x 0.7 kW/m2 of sunlight to each station in both the morning and in the evening for a total of 2 hr x 0.7 kW/m2 of sunlight per day per station.
5.) Combined, the 40 earth stations will produce 5.5 x 40 = 220 GW. Assume that the price for electricity is $0.1 / kWh, annual revenue = $3x10^10 / yr = $16 billion per yr.

Mirror Satellite Constellation Cost
It all depends on launch cost for LEO orbit (Not GEO).
The ISC SPS study (4) assume$400 per kg. SpaceX Falcon Heavy (7) = $1,100 per kg.
   MiraSolar sat (4) cost $0.6 B; constellation (4) $11 B.
   MiraSolar sat (7) cost $1.8 B; constellation (7) $32 B.

Payback time range:
   Assuming 40 ground stations and $400 per kg launch cost: 0.7 years.
   Assuming 40 ground stations and $1100 per kg launch cost: 2 years.
## Space power system comparisons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mirror Sat 2022</th>
<th>Soletta 1978</th>
<th>ISC SPS</th>
</tr>
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<tbody>
<tr>
<td>Orbit</td>
<td>1,000 km</td>
<td>4,200 km</td>
<td>36,000 km</td>
</tr>
<tr>
<td># Satellites</td>
<td>18</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Mirror Area per Sat</td>
<td>78 sq km</td>
<td>462 sq km</td>
<td>12.8 sq km</td>
</tr>
<tr>
<td>Total Mirror Area</td>
<td>1404 sq km</td>
<td>4620 sq km</td>
<td>12.8 sq km</td>
</tr>
<tr>
<td>24 hr/day Earth Power</td>
<td>$18 GW</td>
<td>180 GW</td>
<td>1.2 GW</td>
</tr>
<tr>
<td>GW / Mirror sq km</td>
<td>0.012</td>
<td>0.039</td>
<td>0.09</td>
</tr>
<tr>
<td>Cost ($400/kg)</td>
<td>$11 B</td>
<td>$110 B</td>
<td>$14 B</td>
</tr>
<tr>
<td>$ per 24 h GW</td>
<td>$0.7 B / GW</td>
<td>$0.7 B / GW</td>
<td>$11.7 B / GW</td>
</tr>
<tr>
<td>Earth Station Size</td>
<td>5.5 GW</td>
<td>180 GW</td>
<td>1.2 GW</td>
</tr>
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</table>
Space Mirrors are a common element for large Space Solar Power systems.

Common requirements are:

1. Self deployment
2. Self pointing
3. Sufficient Optical Accuracy
4. Light Weight
5. Durability
JAXA Prior Art – Large Deployable Reflector – In GEO since 2006

**Engineering Test Satellite VIII**

<table>
<thead>
<tr>
<th></th>
<th>Accuracy</th>
<th>Weight</th>
<th>Density</th>
</tr>
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<tbody>
<tr>
<td>LDR for reception</td>
<td>2.4mmrms or less</td>
<td>105kg (reflector)</td>
<td>650g/m²</td>
</tr>
<tr>
<td>LDR for transmission</td>
<td></td>
<td></td>
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Solar Array Paddle
Lightweight Mirrors

L’Garde Solar Sail
250 m x 250 m at 10 g / sq m
Origami in Space: BYU & NASA JPL designed Solar Array (Can be adapted to Mirror Satellite)
Proposed Mirror Satellite Design Concept
Make one that can be launched today & replicated many times as required

| A satellite mirror element is shown with 0.25 km mirror span. The NASA ISC SPS assumes 0.5 km diameter mirrors. This MiraSolar satellite element can serve as an initial test article as well as a repetitive building element. | Each mirror satellite consists of lightweight mirror membranes suspended at 3 points by 3 booms telescoping out from a center body. The center body contains CMGs for attitude control and a solar panel for power. | Control Moment Gyros (CMGs) similar to those used on the international Space Station (shown above) can be used to point the mirror satellite at the desired ground solar power station. |
Thoughts on Origami Mirror Fold Pattern Using Large Flat Panel Segments

Three point support with springs creates light weight optically flat mirror satellite

\[ N = \# \text{ of rows (odd number)} \quad Y = 2 \times X \tan(30) = 1.16X \quad Z = 2 \times X / \cos(30) = 2.3 \times X \quad L = (4N+1) \times X \quad A = 0.435 \times L^2 \]

Example (1): \( A = 1200 \text{ sq m} \quad L = 53 \text{ m} \) suppose \( X = 1 \text{ m} \), then \( N = 52/4 \). Then \( N = 13 \)
Example (2): \( L = 303 \text{ m} \quad A = \text{ approx } 40,000 \text{ sq m.} \) Suppose \( X = 3 \text{ m} \), then \((4N+1)3 = 303\). Then \( N = 25 \)
Self Deploying Mirror Satellite Telescope Sequence
Self Deploying Mirror Satellite Fanning Sequence

Fully deployed area is 60 times larger than stowed area
Minimizing Maneuvers for Durability

Mirror Satellites rotating 7 revolutions per orbit around sun pointing axis can easily acquire & hold on 6 target ground sites with minimal angular momentum adjustments & minimal energy requirements.
Mirror sweep rates for Orbit altitude = 880 km
Standard sweep rate = 7 revolutions per orbit = 7° per orbit degree

<table>
<thead>
<tr>
<th>Deg off vertical (earth center)</th>
<th>Degrees off vertical (ground station)</th>
<th>Delta</th>
<th>Sweep rate Degrees per orbit degree</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16.12</td>
<td>16.12</td>
<td>8.06</td>
</tr>
<tr>
<td>4</td>
<td>30.41</td>
<td>14.27</td>
<td>7.13</td>
</tr>
<tr>
<td>6</td>
<td>42.07</td>
<td>11.66</td>
<td>5.83</td>
</tr>
<tr>
<td>8</td>
<td>51.29</td>
<td>9.22</td>
<td>4.61</td>
</tr>
<tr>
<td>10</td>
<td>58.6</td>
<td>7.29</td>
<td>3.65</td>
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Development Road Map & Perspective

<table>
<thead>
<tr>
<th>Steps</th>
<th>Cost Estimate</th>
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<tbody>
<tr>
<td>1. 1\textsuperscript{st} Mirror Satellite for Moonlight for 4 Disney Parks</td>
<td>$10 Million</td>
</tr>
<tr>
<td>2. 18 Mirror Satellites for Municipal Street Lighting</td>
<td>$70 Million</td>
</tr>
<tr>
<td>3. 18 Mirror Array Constellation for Ground Solar Farms</td>
<td>$15 Billion</td>
</tr>
<tr>
<td>4. 2x18 More Mirror Array Constellations for Solar Farms</td>
<td>$2x11 Billion</td>
</tr>
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Comparison: Three Gorges Dam vs 54 Mirror Array Constellation

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<tr>
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<th>Three Gorges Dam</th>
<th>54 Mirror Array Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost:</td>
<td>$37B</td>
<td>$37B</td>
</tr>
<tr>
<td>Power (24 hour/day):</td>
<td>22 GW</td>
<td>54 GW</td>
</tr>
<tr>
<td>Land Use:</td>
<td>22 GW on 700 sq km</td>
<td>5 GW on 100 sq km</td>
</tr>
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</table>
Development Road Map

Step #1
1st Mirror Satellite for Moonlight for 4 Disney Parks

A 17 m diameter mirror in a 550 km Dawn-Dusk Orbit could give a Full Moon Equivalent Intensity on a 6 km diameter spot on earth.
Conclusions

• A sun synchronous dawn dusk polar orbit is an interesting orbit for mirror satellites.

• Space mirrors in this orbit can build on momentum in terrestrial PV and CSP dramatically reducing cost of solar power from space.

• In any case, similar self deploying and pointing space mirrors are proposed for the NASA SPS ALPHA concept.

• Potential initial concerns about mirror satellite pointing, durability, and optical quality have been addressed.

• The time is right for a more detailed study of space mirror satellites.