Space Solar Power (SSP) Concept and Technology Maturation (SCTM) Program

Space Solar Power: Concept Evolution

Dr. Monica Doyle

Science Applications International Corporation
Schaumburg, IL

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Cleveland, IH

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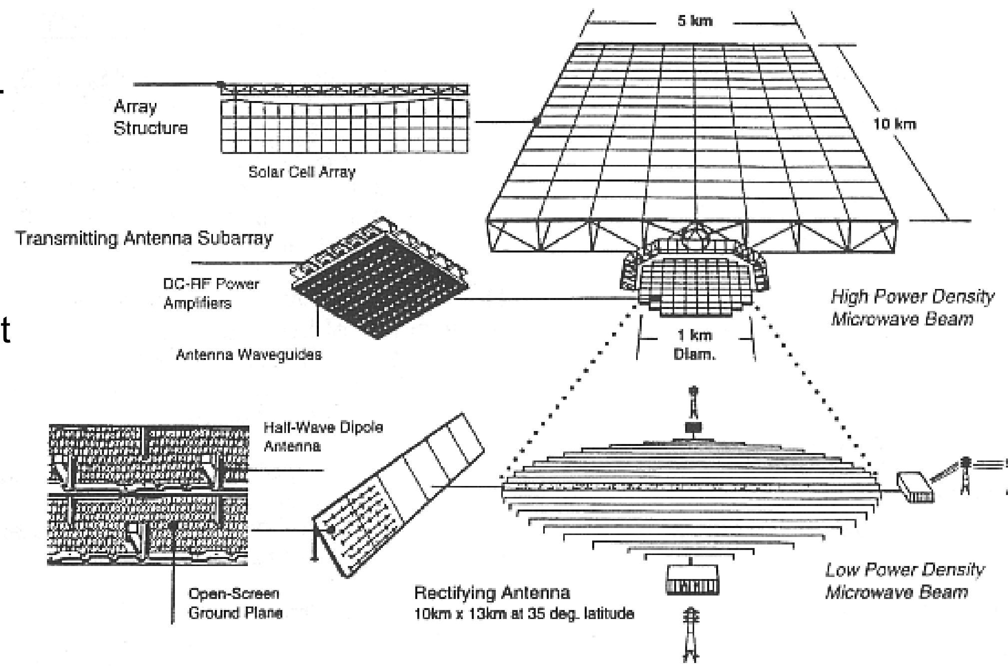
Solar Power Satellite

(1979 SPS Architecture)

- Concept
  - ➢ up to 60 satellites constructed on-orbit and deployed into GEO
  - ➢ each 5 GW system requires 5 km x10 km collecting area and 1 km diameter transmitter
  - ➢ RF power transmission to Earth at 2.45 GHz
  - ➢ structure: compression-stabilized struts & joints



- Issues
  - ➢ on-orbit construction requires:
    - massive construction facility in LEO
    - hundreds of astronauts working continuously over several decades
  - ➢ > $250 billion (FY96) before 1st kW could be delivered

- Conclusions
  - ➢ NRC & OTA concluded SPS was technically feasible but economically unachievable at the time.
  - ➢ NRC recommended continuation of research and a revisit of viability around 1990.

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Fresh Look Study: 1995-97

30+ Proposed Concepts

Downselection Factors:

- Investment cost
- Operations cost
- Technical risk
- Public risk
- Flexibility of service
- Societal benefits
- Adaptability
- Growth capability
- Investment opportunity

Most Promising Concepts

Sun Tower
+ gravity-gradient stabilization
+ modular and self-assembling
– intermittent power implies constellation or multiple ground stations

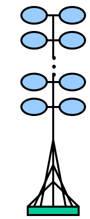
SolarDisc
+ rotationally stabilized
+ self- & robotic assembly, incremental construction
– massive rotary joints, long cable runs
– high technical complexity & investment requirements

GEO Millimeter Wave Dynamic System
+ solar dynamic Brayton cycle
+ mm-wave leads to reduced aperture
– limited power delivery capability
– concerns over reliability & maintenance

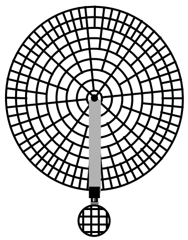
LEO Sun-synch to MEO Equatorial Relay
+ LEO Sun Tower Xmit to MEO relays
– MEO relays require on-board storage & conversion

LEO Sun-synch to GEO Relay
+ LEO Sun Tower Xmit to GEO relays
– fewer relays than in MEO but relays are much larger

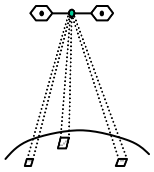
Planetary Power Web
+ Extensive distribution & load leveling
– mature, large scale network of all of the above elements... NOT a viable first step



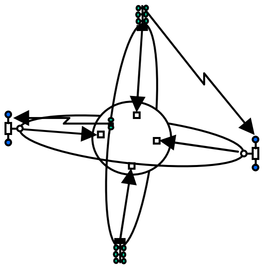
Sun Tower



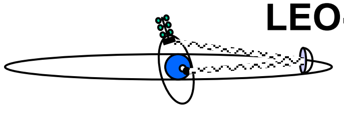
SolarDisc



mm Wave



LEO-MEO Relay



LEO-GEO Relay

Fresh Look Study - Phase II

Concepts added in Phase II

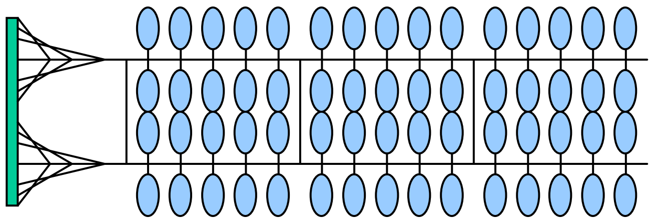
- MEO Sun Tower
  - operational orbit: MEO (6,000 km altitude inclined 30-50 degrees)
  - multiple satellites required to maintain constant power
  - Transmitter (~260m diam.) delivers 250 MW at 5.8GHz, ± 30 degree electronic beam steering
  - ground segment: 4.5 km diam. rectenna
  - collectors must rotate as satellite rolls once per orbit to maintain constant sun-track
- ReflectArray
  - capable of focussing and redirecting incoming RF power beam
  - reflected power can have
    - no power gain (Phase II baseline)
    - limited power gain
    - frequency shift

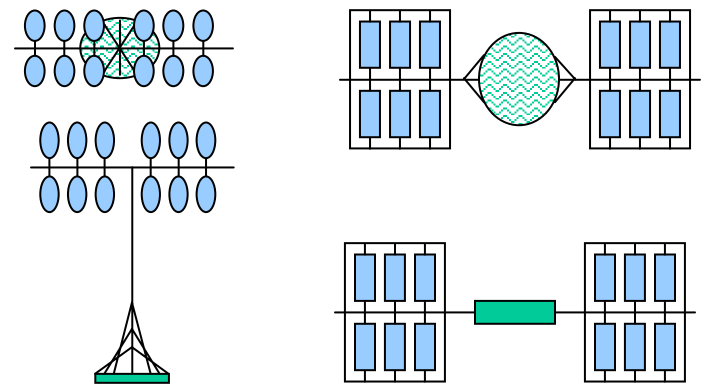
Concept Definition Study: 1997-98

- POD: MEO Sun Tower
  - ➢ GEO Sun Towers
  - ➢ Small GEO Sun Tower (400 MW)
    - Eliminates scan losses associated with MEO design, thereby increasing end-to-end efficiency and decreasing overall mass
    - Provides 24 hour power delivery for most of the year
    - Ground rectenna must be tilted to face satellite
    - Ground rectenna size must grow (relative to MEO Sun Tower) to accommodate the longer transmission distances and the associated power beam expansion
  - ➢ GEO Sun Tower (1.2 GW)
    - Larger transmitter array transmitting higher power & working at the same efficiency as Small GEO Sun Tower requires smaller diameter ground rectenna
    - Estimated launch mass ~ 3x launch mass of Small GEO Sun Tower
  - ➢ New POD = Small GEO Sun Tower

- New / Alternate Configurations...

Dual Backbone Sun Tower & T/POP Configurations (1.2 GW)





Dual Backbone

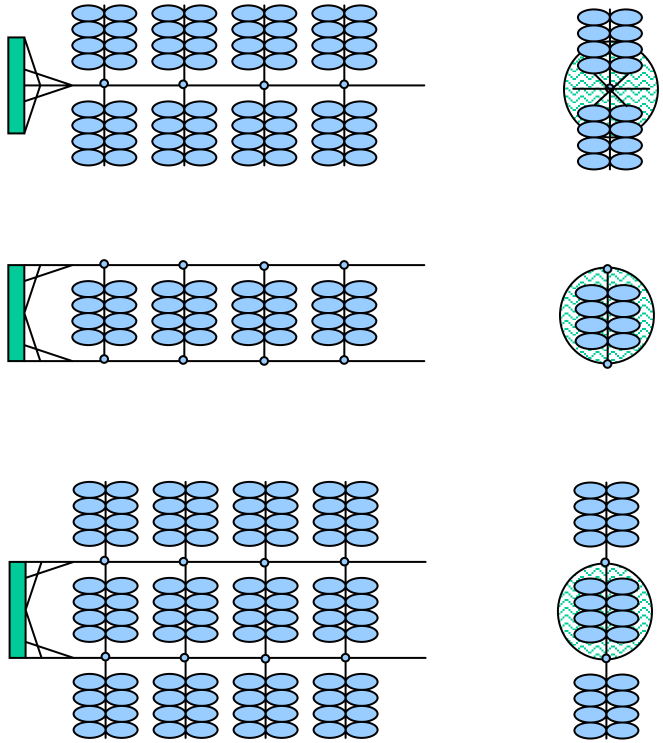
+ reduced cable and structure mass
+ reduction in robotic maintenance & inspection logistics (shorter travel distances)
+ gravity-gradient stabilized in GEO
– larger gyroscopic torques
– roll control for seasonal tracking is more difficult
– structure may be more sensitive to disturbances, structural analysis becomes more complex
– deployment/assembly may be an issue

T/POP Concepts

+ Array shadowing is minimal
+ no seasonal sun tracking roll
+ rotary joint/slip ring connection not required for individual solar arrays
+ reduced cable and structure mass
– no gravity gradient stabilization
– 1 or 2 massive (40-80 MT) rotary joints required to carry power to transmitters (mass may exceed launch vehicle payload limits)
– Each solar array performs seasonal tracking or takes cosine loss (may cause some shadowing)

Additional Sun Tower Derivatives

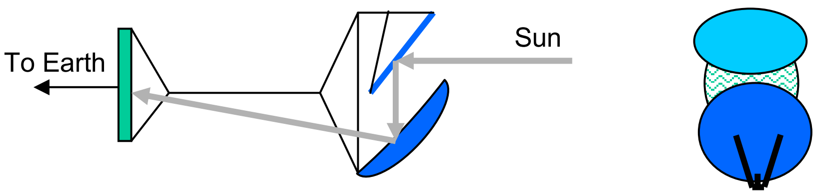
Rigid Boom Subarray (1.2 GW)



- Concept
  - rigidized booms (like T-config.)
  - gravity-gradient stabilized (unlike T), unless backbone length is shortened
  - more compact with less shadowing than single backbone Sun Tower
- Issues
  - mass of rigidized booms may result in larger overall satellite mass
  - massive rotary joint at the base of each subarray
  - packaging for automatic deployment and assembly is difficult

Sandwich Concepts (1.2 GW)

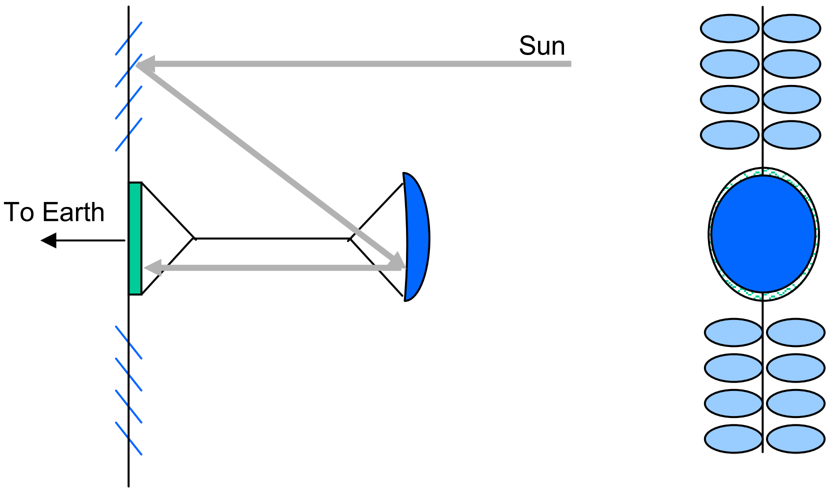
- Concept
  - Avoids mass & efficiency penalties incurred in transporting electricity through long cables and rotary joints.
  - Array collects reflected solar energy on its backside, converts it to electricity then RF energy for transmission from its front panel.
  - Issues include: heat dissipation from the middle layer and assembly & control of the large mirrors.



(a) Single Tracking Mirror

- Single Tracking Mirror
  - complex gravity gradient stabilization
  - requires pointing of very large thin-film structure

- Modular Tracking Mirrors
  - gravity gradient stabilization

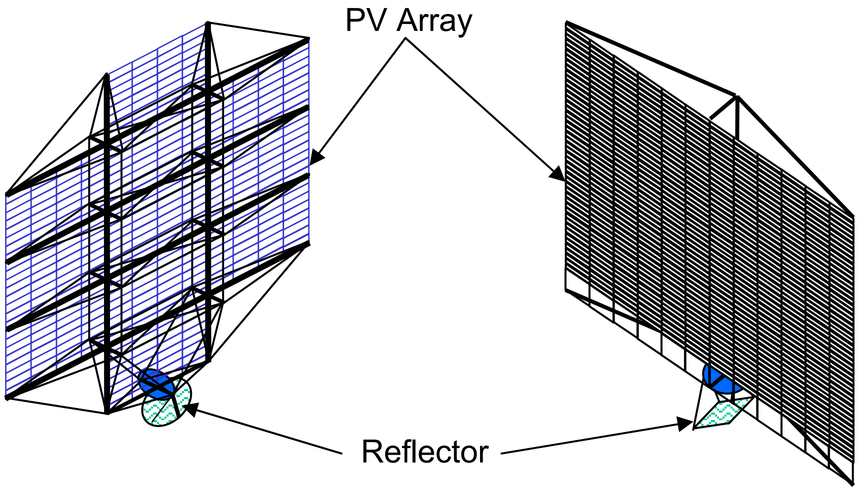


(b) Modular Tracking Mirrors

SSP Exploratory Research and Technology (SERT) Study: 1999-2000

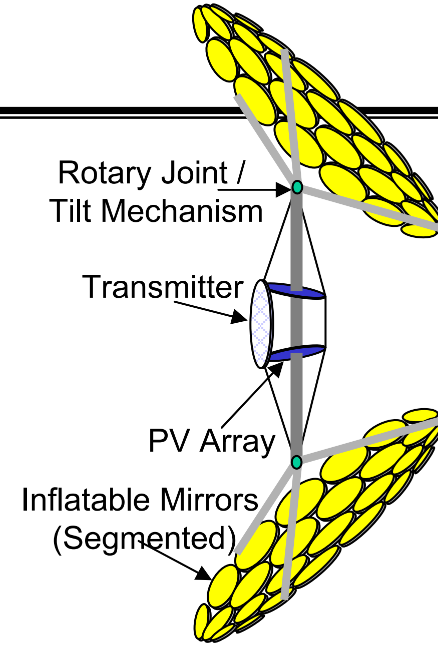
- Goals
  - Develop alternate SSP configurations that would avoid one of the pitfalls of previous designs: the need for rotary joints and slip ring assemblies to carry power from the solar collecting elements to the transmitter
  - Improve the existing modeling tools to encompass the new configurations and new technologies that were being developed
  - Explore SSP concepts using lasers to transmit the collected energy to the ground

SERT Concepts



RF Reflector / Abacus Array

- + RF xmtr rotates with the collecting structure and transmits RF energy to a lightweight, Earth-pointing reflector
- + Reflector tracks the receiving antenna on the ground and redirects the energy to the ground site
- + modularized & rigid structure
- + lightweight deployable reflector mount
- – Challenges associated with the Reflector concept, and the Abacus configuration in particular, include the in-space construction, assembly and/or deployment of the large (~500 m) reflector
- – reflector thermal control may also be problematic



Integrated Symmetrical Concentrator

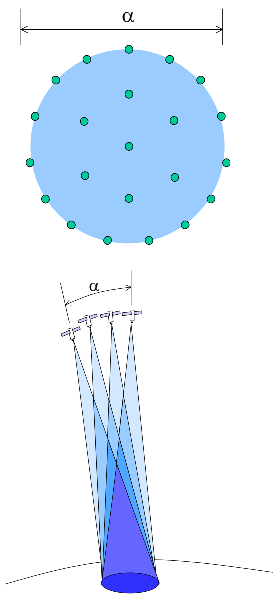
- ➢ sunlight is reflected & concentrated onto the PV arrays by large (Sun-pointing) mirror clamshells and the PV arrays rotate with the Earth-pointing transmitter
- ➢ mirror clamshells are made up of inflatable flat segments
- – primary concern in the ISC design is the dissipation of heat from the back of the PV array
- – uneven illumination of PV array may cause thermal as well as PMAD problems

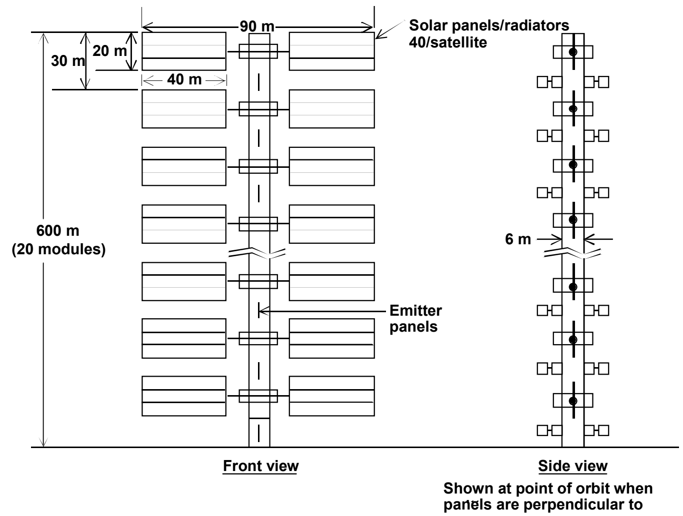
RF vs Laser Power Beaming

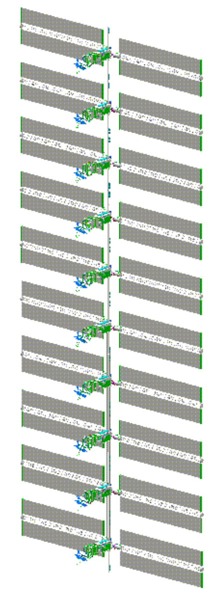
- **RF carries extremely large size requirement**
  - Size drivers: beam steering, grating lobes, ground spot size
  - Transmitter cannot be distributed over smaller "modules"
  - No revenues until the entire system is complete and operational. Large cost-to-first-power will be unattractive to investors
- **Large RF platform increases assembly and Ops costs and PMAD mass**
  - Must be assembled in GEO
  - Dynamics of large flexible structures may be difficult to control
- **Spectrum availability and RFI issues**
- **Massive RF satellite becomes a SPF**
  - Large X-sectional area of the transmitters, reflectors and solar arrays present large targets for micrometeoroids and debris
  - It is not clear that the satellite can remain operational during maintenance periods
- **Public perception of microwave radiation: Fear of Frying**

- **Public concern over eye & skin safety**
  - Can be mitigated by using
    - distributed optical source
    - near IR wavelengths instead of more damaging UV
- **Public concern over use of space-based laser as a weapon**
  - Can be mitigated by
    - requiring a cooperative ground target
    - limiting the spectral density from a single laser to less than one Sun illumination at the target
- **End-to-end efficiency of lasers is much lower than RF SSP systems**
  - Approximate overall efficiencies are
    - RF: 30 - 40 %
    - Laser: 10 %

Laser SSP Configurations







- **UAH Design**
  - Smallest satellite (most satellites per launch)
  - Numerous independent satellites in Halo orbits
  - Can be optimized for 10 Suns and still meet all safety standards
- **Aerospace Corp. Design**
  - 100-200 mid-size satellites in Halo orbits
  - Halo architecture is employed for constellation packing density and to meet laser skin and eye safety standards
  - Can allow multiple Sun illumination operation
- **Boeing Design**
  - Large single satellite (multiple launches per satellite)
  - Gravity gradient stabilized
  - Point source for illumination may violate safety standards

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Current Focus of SSP Activities

- Priority: bring laser concepts up to the same level of maturity as microwave concepts
  - Supported by Committee for the Assessment of NASA's Space Solar Power Investment Strategy, appointed by the NRC
  - Specific improvements in laser technology:
    - increasing laser conversion efficiency
    - improving associated heat rejection systems
    - investigate possibilities of direct solar pumping