ARCHITECTURE OPTIONS FOR SPACE SOLAR POWER

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Abstract

The recent NASA Space Solar Power (SSP) Concept Definition Study considered an architecture known as the Middle Earth Orbit (MEO) Sun Tower. This architecture presents both promise and challenge. Some of the technological challenges of the Sun Tower are specific to that design, rather than to the SSP concept in general, and can be mitigated with alternatives. Promising alternative system configurations are assessed here. The architectures were chosen for their potential to produce economical power in a manner that reduces some of the difficulties associated with the MEO Sun Tower. For each architecture, general system requirements, key technology development requirements, and space transportation requirements are considered. Our assessment suggests that a practical Space Solar Power architecture may evolve over time.

Introduction

During the course of recent Space Solar Power (SSP) studies, many promising system architectures have been suggested. The recent NASA Fresh Look Study[1] was followed by a Concept Definition Study,[2] in which a particular architecture that emerged from the Fresh Look Study was considered in detail. This architecture, the Middle Earth Orbit (MEO) Sun Tower, consisted of a 15-km gravity gradient backbone with 340 pairs of solar collectors. At the bottom of the backbone was a circular 300-m nadir-pointing phased array transmitter that would beam power to the Earth at a frequency of 5.8 GHz. The satellite would be in a circular equatorial 12,000-km orbit. Each satellite would be launched in 340 segments. Each segment would consist of a pair of solar collectors and a portion of the transmitter. The segments would be equipped with a solar electric propulsion system, powered from the collectors, for transfer to the assembly orbit. An economical Earth-to-orbit transportation system capable of handling approximately 30-ton payloads would be required. The MEO Sun Tower serves as a benchmark for comparison with the alternatives described below.

Alternative SSP system architectures continue to show promise, though the technological challenges remain significant. Some of the technological challenges of the MEO Sun Tower are specific to that design, rather than to the SSP concept in general, and can be mitigated with alternatives. Some of the alternative architectures also introduce new challenges. An evaluation of alternative systems is therefore warranted.

Architecture Options

Five promising alternative system configurations are assessed here. The architectures were chosen for their potential to produce economical power in a manner that reduces some of the difficulties associated with the MEO Sun Tower. The variety of configurations considered is fairly wide, with reasonable technological risks (i.e., architectures that require fundamental scientific breakthroughs were not considered). For each architecture, general system requirements, key technology development requirements, and space transportation requirements are considered. The MEO Sun Tower serves as a point of reference, with emphasis given to the significant changes in requirements for the alternative systems. Descriptions of the architectures follow, and are summarized in Table 1.

Architecture 1: GEO Sun Tower

This configuration is similar to that of the Fresh Look Strawman MEO Sun Tower, but it operates at a 36,000-km altitude geostationary Earth orbit (GEO), rather than at 12,000 km. The GEO position allows a single satellite to supply power (almost) continuously to a given receiving station on Earth (Figure 1). This might increase the duty factor and simplify the design of the power transmitter. The total power level, backbone length and transmitter diameter must be resized to compensate for the greater beam divergence from geostationary orbit. However, total power per unit mass is somewhat higher, due to the reduction in scanning loss. In addition, the radiation and debris environment is less severe than in MEO. Space transportation requirements are similar to the

MEO Sun Tower, but a slight increase in propellant per unit satellite mass will be required. Power transmission frequency is 5.8 GHz.

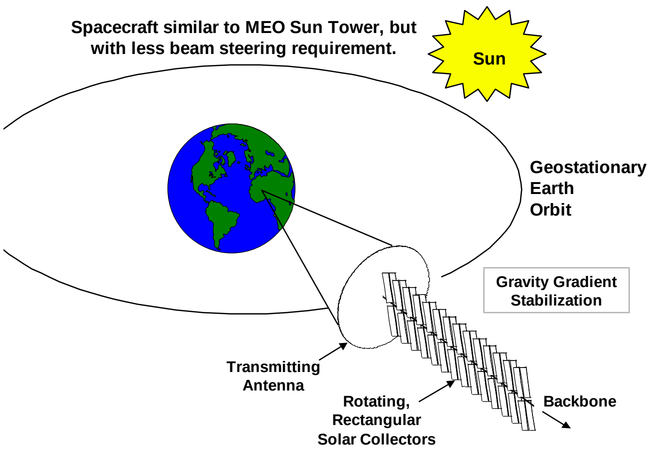

Fig. 1. Architecture 1. GEO Sun Tower.

Architecture 2: "Borealis" Clipper Ship

This configuration consists of an elliptical or circular nadir-pointing transmitter array with long mast-like solar collectors emerging from the top of the array (Figure 2). The solar collectors are non-concentrating thin film cells. This "Borealis"[3] orbit is sun-synchronous and elliptical, with the apogee over the Northern Hemisphere. The collectors will not have to rotate to track the sun. However, large scan angle phased array transmitting antennas will be needed. The power level is roughly comparable to the MEO Sun Tower. However, power cable lengths are much shorter than the 15 km used in the latter's gravity-gradient design. Space transportation requirements are somewhat more challenging, due to the need to launch to a highly inclined orbit. This will require a suitable launch site and greater delta-V. Orbit transfer will require delta-V impulses at perigee, making low-thrust electric propulsion less suitable. Power transmission frequency is 5.8 GHz.

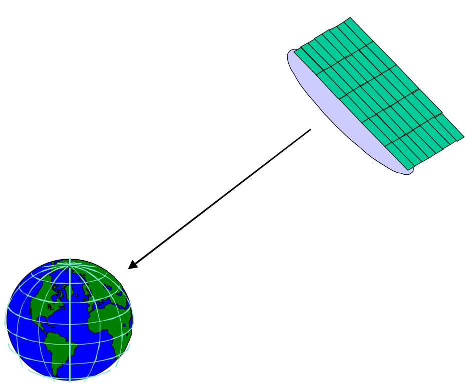

Fig. 2. Architecture 2. "Borealis" Clipper Ship.

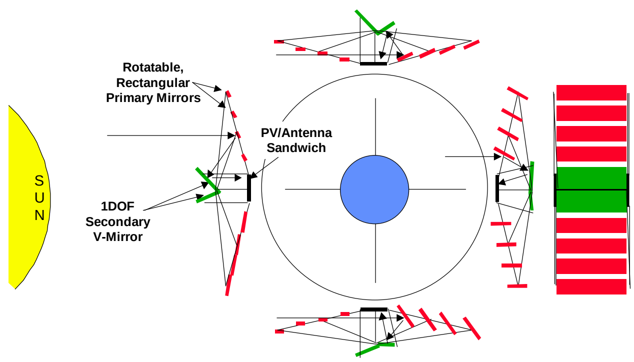

Fig. 3. Architecture 3. GEO Heliostat.

Architecture 3: GEO Heliostat

This is a geostationary configuration consisting of a mirror or system of mirrors that tracks the sun and reflects light onto a power generator/transmitter array (Figure 3). This configuration avoids the use of a long power backbone, thereby reducing the power management and distribution difficulties of the Sun Tower. However, thermal issues may be a greater challenge than for the Sun Tower. The power generation method is presumed to be thermal or photovoltaic. Because the mirrors do not have a power source (unlike the Sun Tower segments), an alternative to integrated electric in-space propulsion will be required for orbit raising. The power transmission frequency is 5.8 GHz. The option of light-pumped laser power transmission is also well suited for this architecture.

Architecture 4: GEO Harris Wheel

This is a geostationary configuration, suggested by Henry Harris of JPL.[4] It consists of a central photovoltaic power generation/transmission system, and a "wheel" of co-orbiting mirrors (Figure 4). The orbits of the mirrors are slightly inclined and eccentric, such that they move in a circle about the generator/transmitter. They do not have to be physically connected. Each mirror controls its

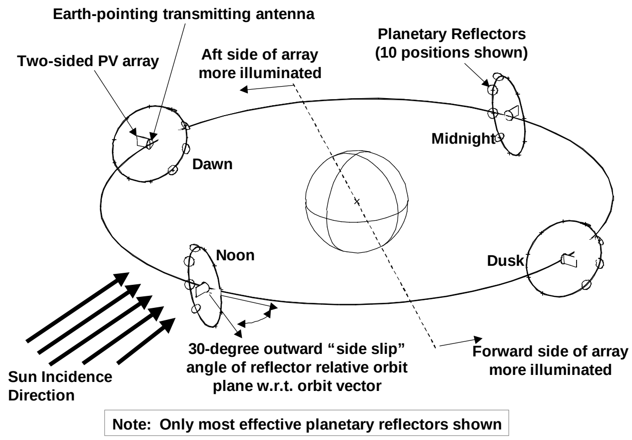

Fig. 4. Architecture 4. GEO Harris Wheel.

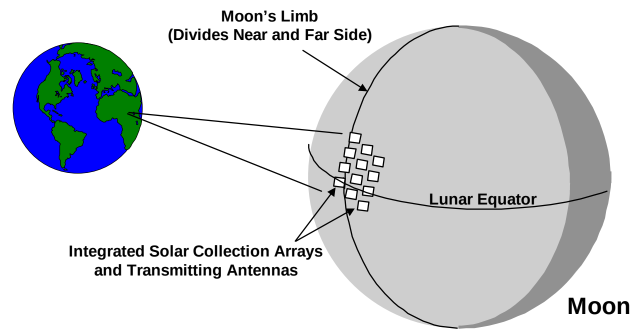

Fig. 5. Architecture 5. Lunar Power System.

orientation to reflect sunlight onto the central power generation system. Like the GEO Heliostat, the power management and distribution difficulties of a long power backbone are avoided. The technology developments required are similar to the GEO Heliostat, with the additional requirements of guidance, navigation, and control and active orientation of a swarm of co-orbiting mirrors. An in-space transportation system for large unpowered segments will have to be developed. Power transmission frequency is 5.8 GHz, though other frequencies, including optical (laser), are possible.

Architecture 5: Lunar Power System

This concept was suggested by David Criswell of the Lunar and Planetary Institute[5] (Figure 5). It consists of arrays of photovoltaic solar collector/microwave transmitter panels on the limbs of the Moon. Since the two stations are on opposite limbs, one or the other is always in sunlight and they both always view the Earth. This system uses the Moon as a stable platform, and a source of raw materials. A lunar mining, processing, and manufacturing infrastructure will therefore be necessary. Because large transmitting arrays are possible, the microwave beams remain tightly focused. Transmission frequency is presumed to be 5.8 GHz, or possibly 2.45 GHz. Power will be available locally only when the Moon is in direct line with the receiving station, unless microwave reflectors are placed in lunar and/or Earth orbit, or a global power distribution system is set up.

Table 1 summarizes the alternatives considered in this study.

Table 1. Architecture Summary.

Ref. No.	Name	Description
0	MEO Sun Tower	Collectors on gravity-gradient-stabilized mast at 12,000 km equatorial orbit. Basis of comparison to others.
1	GEO Sun Tower	Collectors on gravity-gradient-stabilized mast in geostationary orbit.
2	"Borealis" Clipper Ship	Vertical mast-like solar collectors attached to transmitter base.
3	GEO Heliostat	Mirrors reflect sunlight to power generator/transmitter.
4	GEO Harris Wheel	Mirrors in "orbit" around GEO power generator/transmitter.
5	Lunar Power System	Solar collectors and transmitters on lunar surface.

Evaluation of Options

A preliminary assessment was performed which analyzed functional areas and performance metrics, and compared the MEO Sun Tower with the alternative architectures.

Functional areas refer to basic processes that the satellite carries out, including power conversion, power transmission, power management and distribution, orbital parameters, thermal management, and assembly/maintenance activities. Each functional area may have alternatives or variations on the MEO Sun Tower concept. For example, power transmission alternatives include radio frequency (microwave) transmission, and laser transmission.

Performance metrics use traditional means of evaluating a power system, considering factors such as cost per unit power delivered, and cost per installed unit of power. Mass launched per unit power is another metric specific to space systems. Cost to first power is an assessment of the ease of the technological and economic path to the architecture. Technological difficulty combines technology readiness level and research and development degree of difficulty. Global scope refers to the potential of the system to be expanded to supply a large part of the world's needs (i.e., terawatt-level quantities of power). Dual use of technology refers to concepts that use similar technologies for purposes other than direct power (such as deployment of large structures, powering an ion engine for deep-space missions, or radar tracking of near-Earth objects). Dual use of generated power refers to the ability of the system (or technology or infrastructure derived from the system) to supply power for non-terrestrial use. Environmental impact (Earth) refers to the effect of the power system's construction and operation (launch vehicle exhaust, power beam, etc.) on the Earth's biosphere/ atmosphere/ocean system. This includes effects on human beings living and working in the vicinity of rectennas, and elsewhere. Environmental impact (space) refers to the effect of the power system's construction and operation on human activities in space (i.e., through the creation of debris, the effect of microwaves on astronauts, the filling of scarce orbital slots, etc.), as well as to the effect on non-terrestrial bodies (e.g., because of lunar mining). Electromagnetic compatibility and interference (EMC/EMI), though an environmental issue, was considered significant enough to be considered separately. Avoiding interference with communications systems, including satellites in MEO, LEO, and GEO, as well as terrestrial communications and radio astronomy systems, is a major challenge. Value of power delivered is an indication of the temporal and geographic match of the delivered power to the markets.

For each functional area, the approach used in the given architecture is shown. Comments refer to differences from the MEO Sun Tower.

For each performance metric, a "trinary" rating of +, 0, or – was assigned. These are defined as follows:

+: performance is an improvement over that of the MEO Sun Tower;
0: performance is approximately the same as that of the MEO Sun Tower;
-: performance is worse than that of the MEO Sun Tower.

Where the rating was uncertain or debatable, a question mark (?) was noted. In extreme cases, a double rating (++ or --) was used.

For each architecture, the following tables (Table 2.0 through Table 2.5) summarize the functional approaches and the performance ratings. Table 3, which follows the individual architecture rating tables, summarizes the performance ratings for all of the architectures.

Table 2.0. Architecture 0. MEO Sun Tower.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Linear concentrator PV	Split spectrum; goal is 50% efficiency
Power Transmission	5.8 GHz phased array GaN	End-to-end avg. efficiency = 30%
PMAD	100 kV parallel AC	Goal is 90% efficiency
Orbit	12,000 km Equat. circular	
Thermal	Passive	
Assembly/Maintenance	Autonomous	Modular segments

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	0	Goal is 5¢/kWh (MEO Sun Tower is reference for comparison)
Cost/installed watt	0	(MEO Sun Tower is reference for comparison)
Mass launched/ power	0	(MEO Sun Tower is reference for comparison)
Cost to first power	0	(MEO Sun Tower is reference for comparison)
Technological difficulty	0	(MEO Sun Tower is reference for comparison)
Global scope	0	(MEO Sun Tower is reference for comparison)
Dual use of technology	0	(MEO Sun Tower is reference for comparison)
Dual use of generated power	0	(MEO Sun Tower is reference for comparison)
Environmental impact (Earth)	0	(MEO Sun Tower is reference for comparison)
Environmental impact (space)	0	(MEO Sun Tower is reference for comparison)
EMC/EMI	0	(MEO Sun Tower is reference for comparison)
Value of power delivered	0	(MEO Sun Tower is reference for comparison)

Table 2.1. Architecture 1. GEO Sun Tower.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Linear concentrator PV	
Power Transmission	5.8 GHz phased array GaN	Avg. eff. increased to 40% (no scan loss)
PMAD	100 kV parallel AC	Longer backbone
Orbit	Geostationary	Fixed over gnd. station – 100% coverage
Thermal	Passive	Less thermal cycling
Assembly/Maintenance	Autonomous	Modular segments

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	+	Higher power transmission duty cycle
Cost/installed watt	0	Better transmit efficiency, but higher altitude
Mass launched/ power	+	100% duty cycle & no scan loss
Cost to first power	-	
Technological difficulty	0	
Global scope	+	More room in GEO; more Earth surface visible
Dual use of technology	0	
Dual use of generated power	0	
Environmental impact (Earth)	+	No beam slewing
Environmental impact (space)	+	Less debris and lower velocity collisions
EMC/EMI	+	No beam slewing
Value of power delivered	+	Can choose GEO slot to match need for power

Table 2.2. Architecture 2. "Borealis" Clipper Ship.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Non-concentrator PV	
Power Transmission	5.8 GHz phased array	Antenna rocks relative to horizon
PMAD	100 kV parallel AC	
Orbit	"Borealis" sun-sync ellipse	
Thermal	Passive	No cycling
Assembly/Maintenance	Autonomous; modular	More difficult dynamics

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	+	Continuous sun and more time over rectenna
Cost/installed watt	0	More difficult orbit launch; easier orbit transfer
Mass launched/ power	+	Smaller antenna
Cost to first power	+	Smaller antenna & rectenna, so smaller system
Technological difficulty	0	
Global scope	+	Access to higher latitudes
Dual use of technology	0	
Dual use of generated power	0	
Environmental impact (Earth)	0	
Environmental impact (space)	-	Debris collision potential
EMC/EMI	+	Closer; less slewing
Value of power delivered	+	

Table 2.3. Architecture 3. GEO Heliostat.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Thermal/PV	Converter on transmitter element
Power Transmission	5.8 GHz phased array	Candidate for solar-pumped laser
PMAD	Mirrors	High efficiency
Orbit	Geostationary	
Thermal	Active?	
Assembly/Maintenance	Autonomous; modular	

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	0?	
Cost/installed watt	0?	
Mass launched/ power	+?	
Cost to first power	-	Bigger system
Technological difficulty	-	
Global scope	+	More room in GEO; more Earth visible
Dual use of technology	0?	
Dual use of generated power	0	
Environmental impact (Earth)	+	No beam slewing
Environmental impact (space)	+	Less debris and lower velocity collisions
EMC/EMI	+	No beam slewing
Value of power delivered	+	Can choose GEO slot to match need for power

Table 2.4. Architecture 4. GEO Harris Wheel.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Concentrator PV	
Power Transmission	5.8 GHz phased array	Solar-pumped laser possible
PMAD	Mirrors	
Orbit	Geostationary	
Thermal	Active?	
Assembly/Maintenance	Autonomous; modular	

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	0?	
Cost/installed watt	0?	
Mass launched/ power	+?	
Cost to first power	-	Bigger system
Technological difficulty	- -	
Global scope	+	More room in GEO; more Earth visible
Dual use of technology	0?	
Dual use of generated power	0	
Environmental impact (Earth)	+	No beam slewing
Environmental impact (space)	0	Less debris and lower velocity collisions than in lower orbits, but more spacecraft than in other GEO architectures
EMC/EMI	+	No beam slewing
Value of power delivered	+	Can choose GEO slot to match need for power

Table 2.5. Architecture 5. Lunar Power System.

Functional Area Assessment		
Function	**Approach**	**Comments**
Power Conversion	Non-concentrator PV	Uses in-situ materials
Power Transmission	5.8 GHz phased array	
PMAD	Integral	
Orbit	On lunar surface	
Thermal	Passive	
Assembly/Maintenance	Von Neumann machines	

Performance Ratings		
Criterion	**Rating**	**Comments**
Cost/power delivered	+	
Cost/installed watt	+	Uses in-situ materials
Mass launched/ power	+	Mass launched from Earth is low, due to in-situ materials use
Cost to first power	- -	Extremely high
Technological difficulty	- -	Must develop lunar infrastructure
Global scope	+ +	Could provide most of Earth's energy needs
Dual use of technology	+	Space exploration
Dual use of generated power	+	Lunar bases
Environmental impact (Earth)	0	
Environmental impact (space)	-?	Mining/industry affects lunar surface, but does not create orbital debris
EMC/EMI	0	
Value of power delivered	-	28-day illumination cycle; power on Earth only when Moon is in view

Table 3. Summary of Evaluations.

Architectures → Criteria –	Arch. 0: MEO Sun Tower	Arch. 1: GEO Sun Tower	Arch. 2: "Borealis" Clipper Ship	Arch. 3 GEO Heliostat	Arch. 4: GEO Harris Wheel	Arch. 5: Lunar Power System
Cost/power delivered	0	+	+	0?	0?	+
Cost/installed watt	0	0	0	0?	0?	+
Mass launched/power	0	+	+	+?	+?	+
Cost to first power	0	-	+	-	-	- -
Technological difficulty	0	0	0	-	- -	- -
Global Scope	0	+	+	+	+	+ +
Dual use of technology	0	0	0	0?	0?	+
Dual use of generated power	0	0	0	0	0	+
Environmental impact (Earth)	0	+	0	+	+	0
Environmental impact (space)	0	+	-	+	0	-?
EMC/EMI	0	+	+	+	+	0
Value of power delivered	0	+	+	+	+	-

Conclusions

This assessment was intended to be broad in scope, with consideration given to a wide range of alternative systems. It can serve as a starting point for more detailed analysis of proposed architectures, and possibly additional variations. In comparing the ratings of alternatives, it appears that the GEO Sun Tower (1) and "Borealis" Clipper Ship (2) may be preferable to the MEO Sun Tower (0). GEO Heliostat (3) and Harris Wheel (4) alternatives also appear to improve upon the Sun Tower, but have a higher degree of uncertainty. The Lunar Power System (5) has the highest costs and difficulty, but also has the highest potential to supply a significant part of the world's energy over the long term. Considering that the cost to first power is a driver for implementing SSP systems, the foregoing comparison suggests that a practical SSP architecture may evolve as follows, over time:

A) For near-term system-level demonstrations, a system in a low-altitude sun-synchronous orbit (e.g. "Borealis") appears to have the lowest cost, with a reasonable potential for commercial utility.

B) For moderate-scale, local power generation in the next century, larger GEO systems seem to be the most practical.

C) For very large-scale, global utility of SSP by future generations, lunar surface systems appear to have the greatest potential. With such a phased implementation approach, Space Solar Power may grow from initial, affordable system demonstrations to interim commercial applications, and eventually to achieve low-cost global utilization.

References

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