

IAC-02-R.4.08

WIRELESS POWER TRANSMISSION OPTIONS FOR SPACE SOLAR POWER

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World Space Congress,
Houston; Texas, USA
Oct. 17, 2002**

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Abstract:

Space Solar Power (SSP), combined with Wireless Power Transmission (WPT), offers the far-term potential to solve major energy problems on Earth. In this paper two basic WPT options, using radio waves and light waves, are considered for both long-term and near-term SSP applications. In the long-term, we aspire to beam energy to Earth from geostationary Earth orbit (GEO), or even further distances in space. Accordingly, radio- and light- wave WPT options are compared through a wide range of criteria, each showing certain strengths.

In the near-term, we plan to beam power over more moderate distances, but still stretch the limits of today's technology. For the near-term, a 100 kWe-class "Power Plug" Satellite and a 10 kWe-class Lunar Polar Solar Power outpost are considered as the first steps in using these WPT options for SSP. By using SSP and WPT technology in near-term space science and exploration missions, we gain experience needed for sound decisions in designing and developing larger systems to send power from Space to Earth.

Introduction

The demand for power on Earth is growing exponentially, and associated environmental consequences are becoming significant. In this new century, Space Solar Power (SSP) may provide a clean, safe energy source, alleviating some of the problems we would otherwise expect from increasing nuclear and fossil fuel use.

Satellite photographs of the Earth at night are, effectively, a means of remote sensing for power consumption, in the form of electric lights. Figure 1 is a composite satellite photograph showing the entire Earth at night, lit up by our current levels of power consumption (as of November, 2000). Bright areas define power-rich population centers, generally concentrated near coastlines and waterways (note the brightness of the Nile river in Egypt). Some of the dark regions indicate barren deserts, while

others, like sub-Saharan Africa, are well populated, but power-starved. Deserted locations adjacent to populated regions are potential sites for future large WPT receiving stations.

Comparison of WPT Options for Far-Term SSP Systems

Wireless Power Transmission uses electro-magnetic waves, rather than wires, to send energy from one location to another. Two basic alternatives are being considered for power beaming: radio waves (microwaves) and light waves (lasers).

Radio waves are beamed in a cloud-penetrating radio-frequency band reserved for Industrial, Scientific and Medical (ISM) applications). Figure 2 illustrates an example SSP concept using the 5.8 GigaHertz ISM band; in this case, a 500 meter diameter phased array transmitting antenna directs radio waves from GEO to a 7.5 kilometer diameter rectifying antenna on Earth, approximately 40,000 km away from power receiving stations. Here, a 15 kilometer long, gravity gradient-stabilized "backbone" carries 2.8 GigaWatts of power from the solar panels down to the transmitter. Following a wide variety of loss mechanisms (pointing, side-bands, filtering, power conversion, etc.) the system provides 1.2 GigaWatts of electrical power on Earth.

Light waves are beamed in a wavelength which can be generated efficiently and easily transmitted through the atmosphere in an optical or infra-red "window". Figure 3 illustrates an example SSP concept using lasers, instead of microwaves, to transmit the

same peak power level on Earth (1.2 GWe). Laser-Photovoltaic wireless power transmission is currently less efficient (by about 50%), so a larger solar array area is needed to collect sunlight, and the satellite becomes much longer (55 km), and about half as wide. WPT is provided by a series of small laser transmitters running the entire length of the satellite. Each light beam has a relatively small diameter, so each diverges relatively rapidly, but their combined energy fills a large diameter (6 km), dual-use photo-voltaic receiver on Earth with roughly 500 W/m² of monochromatic light. This is half the peak intensity of sunlight on Earth (~1 kW/m²), but, because the WPT wavelength can match the photo-voltaic cell's band-gap, the cell's efficiency can be much higher (e.g., >40% vs 20% efficiency). Photovoltaic electrical power output may actually be greater with WPT than with sunlight, even though the sunlight is twice as powerful.

Laser-photovoltaic WPT systems do not require large transmitter apertures, so the same net effect (1.2 GWe on Earth) could be provided by a large number of smaller, co-orbiting satellites.

Figure 4 summarizes key features of a dual-use photo-voltaic receiver. Large photovoltaic power plants in major deserts areas can receive & convert light both directly from the Sun, and via WPT from the SSP satellite(s). Gravity gradient-stabilized SSP satellites receive the most sunlight, and transmit the most power around 6 AM and 6 PM. Around mid-day and midnight, solar panel self-shadowing or cosine losses significantly reduce the power output. The combination of ambient sunlight (which peaks around mid-day) plus WPT

illumination combines at the terrestrial PV array to match the daily electricity demand pattern.

A satellite without gimballed arrays further improves the match between power output and power demand. Gimballed solar panels are heavy and complex, and would add only a little more power around mid-day and midnight. Instead of using gimballed arrays, both sides of rigid (not gimballed) solar arrays can produce power, although the "back" side produces less power due to occlusion by wires, and partial transmission of sunlight through the translucent substrate (e.g., Kapton). By placing the "back" side facing the morning sun (East) and the "front" side facing the afternoon sun (West), the satellite's power output is more closely matched to typical terrestrial power market demands, which have a higher peak in the afternoon than in the morning.

This type of combined system has other far-reaching benefits when compared to a typical terrestrial solar-photovoltaic (PV) system. Typical terrestrial PV installations would require a much larger area to collect power, and would need power storage systems, with large conversion losses, to match the electricity demand. By combining the natural time-dependent output of direct solar-PV and SSPWPT-PV systems, both can benefit.

Significant attributes of far-term SSP systems for radio-wave and light-waves WPT are compared in figure 5 and discussed below:

WPT aperture size must be much, much larger for radio waves, as the WPT

wavelength is close to a million times larger (centimeters vs nanometers). Light-wave WPT allows small initial demonstration systems to be made and tested over significant distances, whereas radio wave WPT requires a huge leap of faith (literally and figuratively) to produce an initial SSP system.

Radio Frequency Interference is also a major drawback for WPT using radio waves. With so much power being produced, even a small fraction outside the ISM band-gap can create major problems for the users of neighboring and harmonic radio frequency bands. The addition of filters is expected to be necessary, which reduces the WPT efficiency and increases local heating.

Radio waves, at 5.8 GHz, (or, even better, at the longer wavelength 2.45 GHz ISM Band) can penetrate through clouds and light rain; light waves, in contrast, are easily stopped by weather phenomenon, and require a dry site, preferably at high altitude. While there is some logic to placing photo-voltaic WPT receivers in desert areas (e.g., inexpensive, otherwise unproductive land), not all areas that need power are near deserts. Power demands in many countries tend to peak when the sun is bright (e.g., for summer air conditioning), which corresponds to relatively clear skies. Nonetheless, WPT using light from an SSP system may require alternate receivers to make good use of the system on cloudy days.

Some legal issues are raised by both systems. Radio wave WPT implies some degree of RF interference, and spectrum allocations and power limits may need to be re-negotiated. Light

wave WPT can be designed to limit the intensity to safe, uncontroversial levels, but the wording of treaties relating to the use of beamed energy for defense applications would need to be reviewed carefully, to determine relevance and ensure compliance, where appropriate.

Infrastructure utilization appears better for light wave WPT, considering the reduced land area and dual application of the photo-voltaic receiver for terrestrial solar as well as SSP-WPT applications.

Other kinds of dual use have been hypothesized for both WPT options. RF WPT could potentially be used for data transmission, and the land beneath receiving antennae could potentially be used to grow crops. A light-beaming SSP system could, hypothetically, be used to send power to orbital transfer vehicles, or even to solar sails (in the very far-term).

Public perception is an issue for either option. The radio frequencies suggested are within the "microwave" band, and the public tends to perceive microwaves as something to cook with. Similarly, the public may perceive power transmission by light to be dangerous, even though the system is designed to ensure safety. Both the micro-wave and light-wave intensity limits suggested are weaker than sunlight.

To ensure public safety (and safety of the receiver from public interference or vandalism), either WPT option would need to be sequestered. It is unclear as to what effects might occur to local flora and fauna from long term exposure within the receiver site. One might expect that a slightly warmer environment, with local shelter, might

attract certain types of wildlife. Radio-frequency coupling may be more prone to transfer energy into small animals, whose body length is comparable to the wavelength. Infra-red WPT light falling on an area over a prolonged time might similarly change the localized plant growing season.

Efficiency is currently higher for radio-wave wireless power transmitters and receivers. Light wave transmitter and receiver efficiency is rapidly improving, but it is not clear whether it will ever approach the efficiency of radio frequency transmission. The combined system efficiencies expected for radio-wave WPT have been matured through related radar and communications applications, and are expected to be in the range of 60-70%, when filtering losses are included. For Laser-PV WPT, the best we expect to achieve about 50%, though this might be improved significantly, as the technology matures through SSP-related flight demonstrations. When power management and distribution losses are considered, there is another impact to net efficiency (and mass) for radio-wave WPT, as electricity is carried to a large central transmitter via wires that are many kilometers long.

Near Term Space Flight Demonstrations

Initial applications of WPT technology in space may use experimental spacecraft. Two early flight demonstrations are being considered as Model System Configurations for Space Solar Power. One concept is concept known as a "Power Plug", or "LAMP" spacecraft, a ~100 kWe space-based power beaming system whose primary

mission is to supply power to its own solar electric propulsion system and to other spacecraft using WPT. A second concept is a Lunar Lander which descends to a mountaintop at the moon's North or South pole, and transmits power to a robot operating in permanently shadowed lunar polar craters.

A general view of one Power Plug concept is illustrated in figure 6. In this case, to achieve the required power level in the near-term with minimal risk, the configuration improved upon the Integrated Energy Assembly (IEA) which is now operating on the International Space Station. Figure 7 is a photograph of this existing power system, the largest space solar power arrays ever built (so far). With minor modifications, and using current state of the art photo-voltaic cells, the power produced by the IEA can be doubled, while keeping many of the existing, flight-proven structures and mechanisms.

A derivative of this experimental spacecraft could be launched on a Delta IV-class launch vehicle to Earth escape velocity (with optional lunar gravity assist swing-by(s)) and proceed into a trans-Mars injection trajectory using solar electric propulsion (SEP). It would again use SEP to enter Mars stationary orbit, where it collects solar energy and beams it to a Mars surface infrastructure. Because of the distance involved (17,038 km altitude), radio-wave WPT would require huge transmitters and receivers, so laser wavelengths are anticipated for WPT, with a beam diameter on the order of meters (rather than kilometers), delivering an average 10 kWe of power to the surface. Because it may support

both lunar and Mars exploration, this concept (figure 8) has been referred to as the Lunar And Mars Power spacecraft, or LAMP.

NASA and Boeing are cooperating to assess a mission that will use SSP and WPT technologies to investigate the anomalous high concentration of hydrogen observed around the poles of the moon. Figure 9 provides an overview of this mission: A solar power generation outpost is landed and deployed on a high peak near the North or South Pole of the moon. The landing site is chosen carefully so that outpost remains in full sunlit over many months (or even years) as the moon rotates once per month around its slightly inclined axis. Landing site selection also considers direct, line-of-sight communications with Earth, and local terrain features that might obstruct Wireless Power Transmission. WPT technology is used to send a significant part of this power to a telerobotic lunar roving vehicle, which is then able to operate in deep dark craters that are thought to contain ice. For example, with a beam of light, longer distance WPT can be achieved from a transmitter on the lander, perhaps using small relay mirrors to redirect the beam into any regions obstructed by local topography. More detail on this mission can be found in a companion paper, "Space Solar Power Technology Demonstration for Lunar Polar Applications" (IAC-02-R.4.04).

Summary

This discussion of Wireless Power Transmission Options for Space Solar Power has made the following key observations:

Far-term micro-wave WPT options are efficient, and beam power through clouds / light rain, but require large sizes for long distance WPT and a specialized receiver, a rectifying antenna or "rectenna".

Far- (or intermediate-) term Laser-Photovoltaic WPT options are less efficient, but have certain system level benefits. They allow a smooth transition from conventional terrestrial solar power to SSP, in part because synergistic use of the same photo-voltaic receiver on Earth can convert both laser-light and sun-light into electrical power. The smaller aperture size also allows smaller (lower cost) initial systems.

Laser-Photovoltaic WPT systems open new SSP architecture options. Efficiency of current / near-term Laser-Photovoltaic WPT technology would seem to indicate higher mass, but specific power may be competitive for laser systems, as their smaller apertures minimize subsystem masses for WPT and power management and distribution. Narrow light beams can also overlap to generate a "top hat"

energy profile, which allows for better use of land at receiver sites. To mitigate weather outages, multiple receiver sites, in desert areas, may be necessary.

Gravity gradient-stabilized "Sun Tower" SSP satellites may make more sense for WPT light-waves than for microwave systems, because the receiver also converts ambient sunlight into electricity. This additional sunlight can correct for the cosine loss otherwise observed in power production at mid-day. With this WPT option, rigid SSP arrays, with both sides able to convert sunlight to electricity, may be preferable to rotating (gimbaled) arrays, as the resulting power produced on Earth can match the typical daily energy demand.

SSP and WPT technology flight demonstrations can enable advanced space science and exploration in the near term. The "Power Plug" or "LAMP" spacecraft and the Lunar Polar Solar Power outpost are two near-term applications that can advance technology for far-term commercial SSP systems, while providing significant value for near-term applications.

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Wireless Power Transmission Options for Space Solar Power

IAC-02-r4.08

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**World Space Congress
Houston, Texas**

October 17, 2002

Wireless Power Transmission Options for Space Solar Power

- Far Term Space Systems to beam power to Earth
 - Radio-Wave WPT System
 - Light-Wave Systems
- Near term Technology Flight Demonstrations
 - Model System Concept 1A: 100 kWe satellite
 - Model System Concept 1B: 10 kWe lunar system

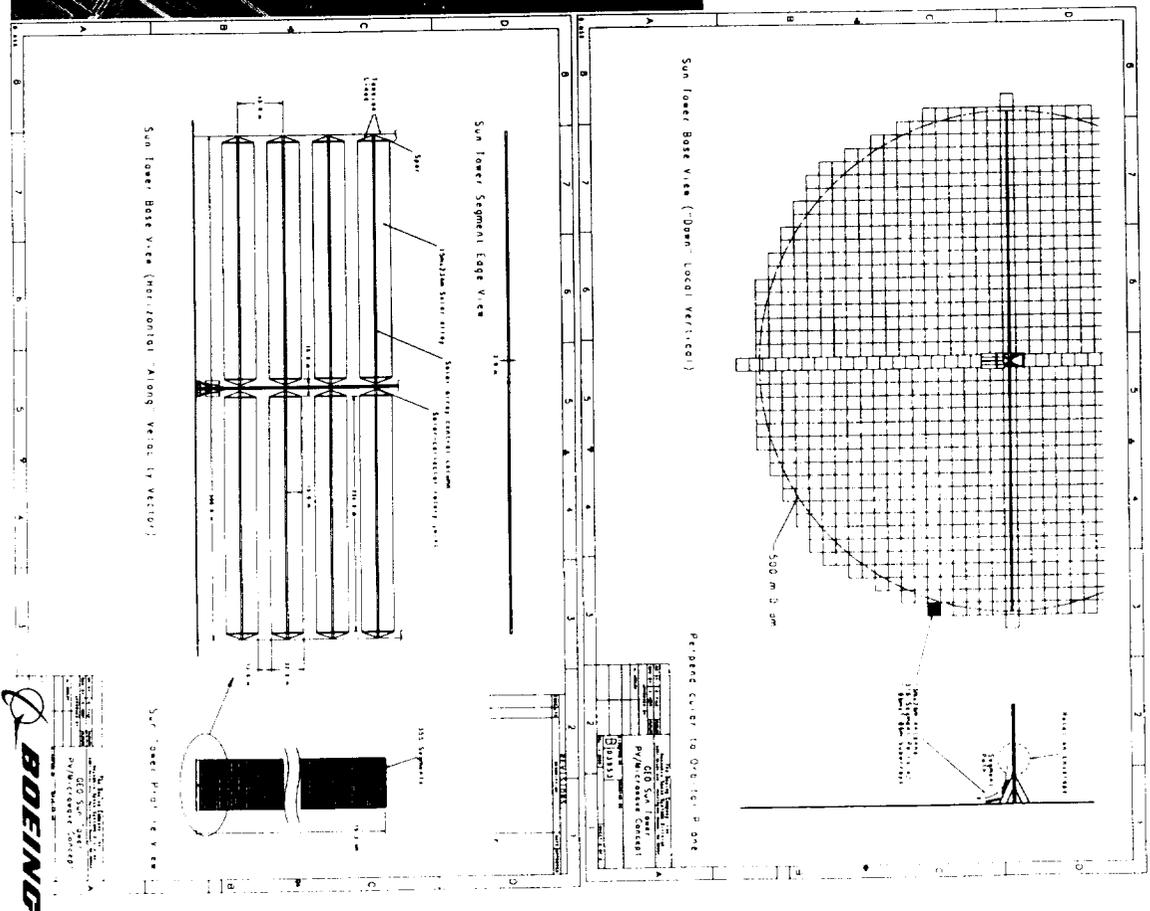
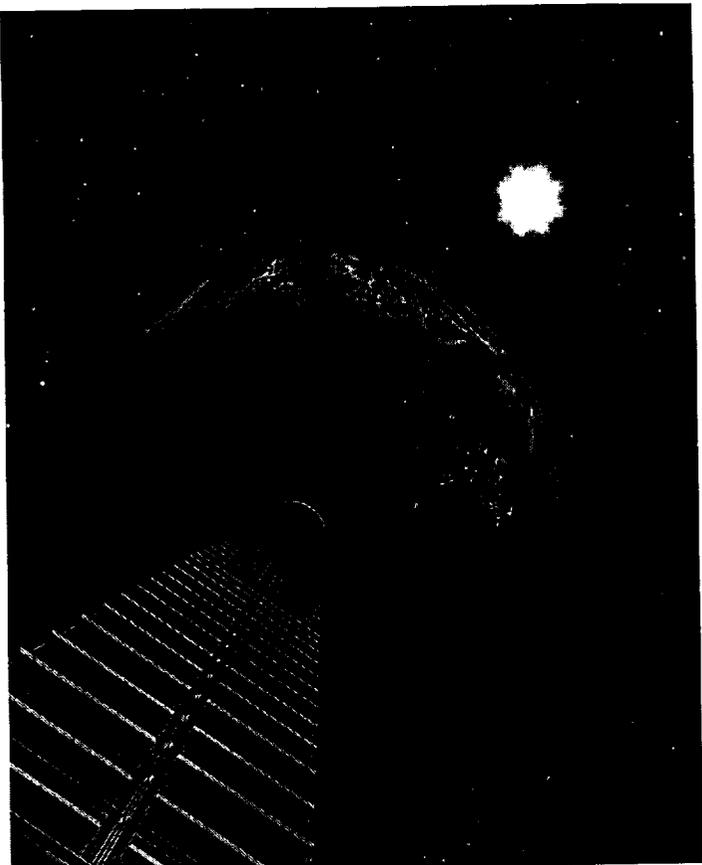
Global Power Consumption



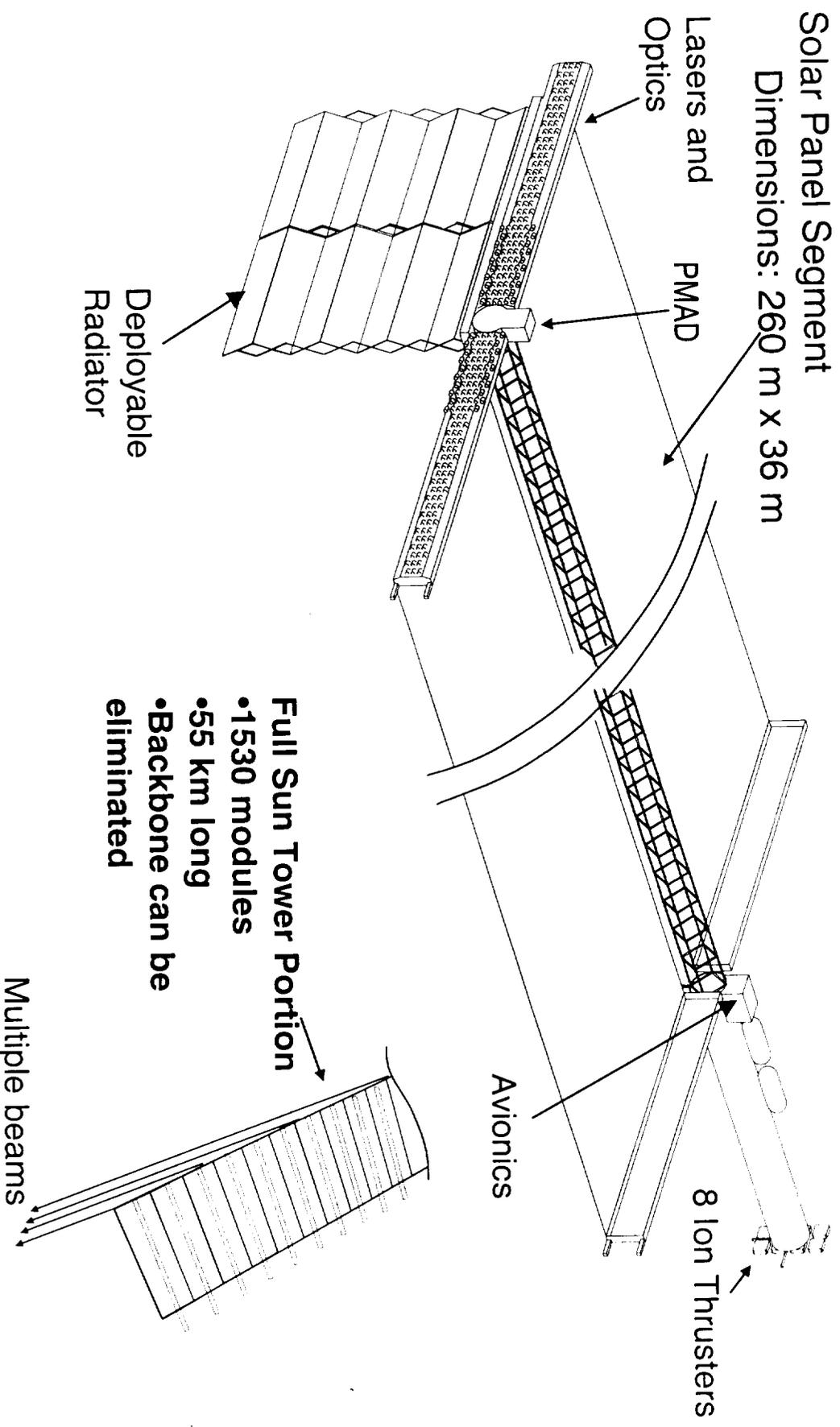
Remote Sensing of Current Global Power Consumption:
A Composite Satellite Photograph of the Earth at Night

Initial Photovoltaic / Microwave SPS GEO Sun Tower Conceptual Design

- Design followed Fresh Look Study
- 500 meter diameter transmitter
- 15.3 km length (gravity gradient)
- 355 identical satellite segments
- Autonomous assembly in GEO
- Large rectenna receivers on Earth



Photovoltaic / Laser-Photovoltaic SPS GEO Sun Tower-Like Concept

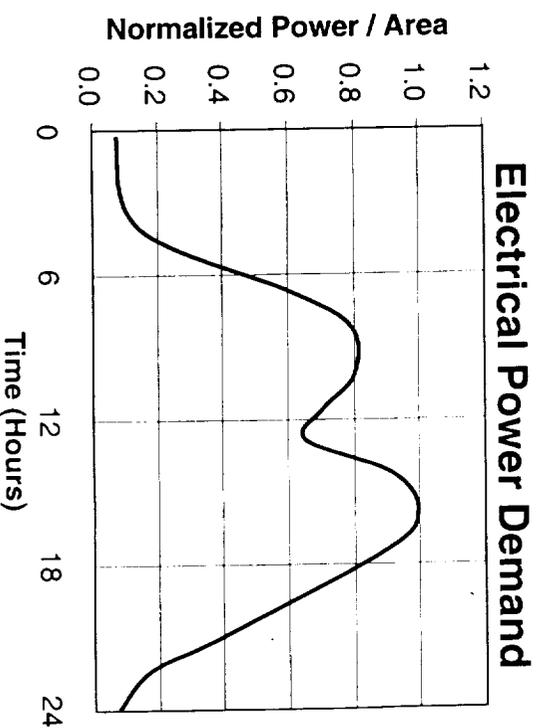
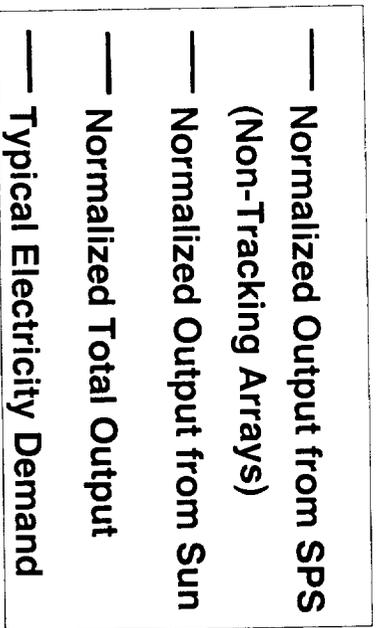
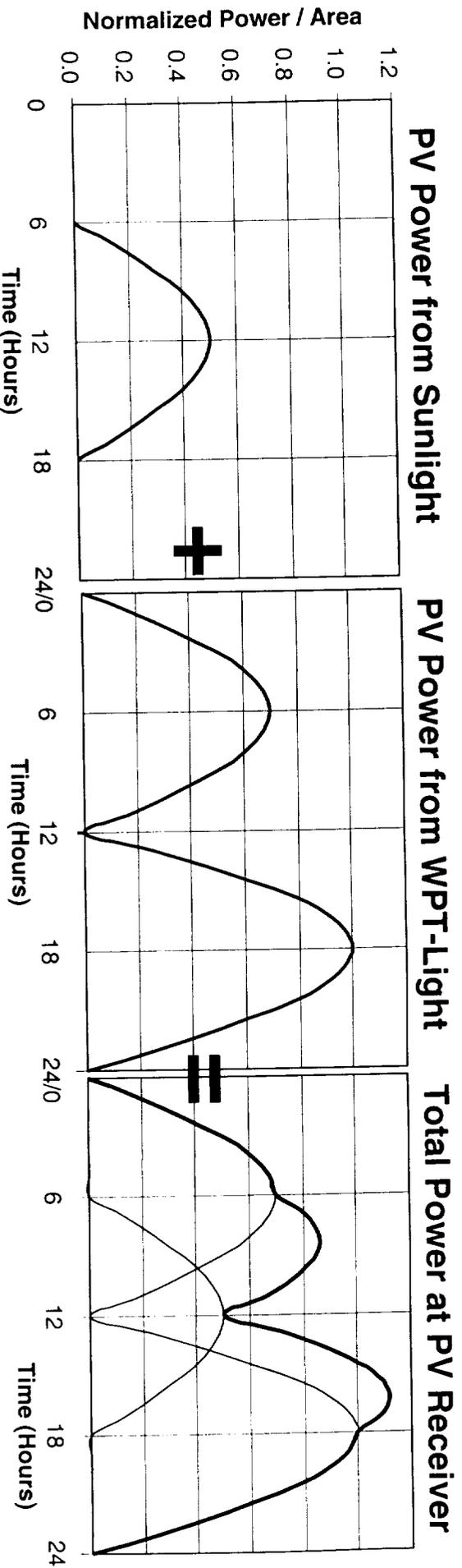


Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

- Large photo-voltaic (PV) power plants in Earth's major deserts (Mojave, Sahara, Gobi, etc.) receive & convert light from 2 sources:
 - 1) directly from the Sun, and
 - 2) via WPT from SSP systems
- Laser light is transmitted and converted more efficiently than sun-light
 - Wavelength is selected for good atmospheric transmissivity
 - Efficient Light Emitting Diode wavelengths match common PV band-gaps
- Gravity gradient-stabilized SSPs are in peak insolation at ~6 AM and ~6 PM, with shadowing or cosine loss at mid-day and midnight
 - Heavy, complex gimbaled arrays add little extra power at these times
 - Both sides of rigid (not gimbaled) solar arrays can be light-sensitive
 - Back-side produces less power due to occlusion by wires
 - Translucent substrate (e.g., Kapton) also reduces back-side power levels
 - Even gimbaled arrays suffer a loss of power around noon and midnight
- The combination of ambient sunlight plus laser illumination combines, at the terrestrial PV array, to match the daily electricity demand pattern

Sunlight + Laser-PV WPT = ~ Power Requirement

Photo-Voltaic (PV) Power Station Receives Both



WPT Wavelength Trade for SSP

ATTRIBUTE	WPT Using Radio Waves	WPT Using Light Waves
Aperture Size	Large. So system must be large	Small; allows flexible system design
Interference	Radio Frequency Interference	None, except perhaps astronomy
Attenuation	Penetrates clouds and light rain	Stopped by clouds (need desert area)
Legal Issues	FCC, NTIA, ITU	ABM treaty, if power density high
Infrastructure	Rectenna useful for SSP only	PV array for both WPT & solar power
Dual Use	Crops?; communications?	PV arrays on rooftops; "solar"-sails?
Perception	Public fears of "cooking"	Government fears of "weapons"
Safety	Safe (must keep aircraft out of beam)	Safe (WPT light intensity < sunlight)
Efficiency (space)	High	Improving
Efficiency (ground)	High	Improving
Traceability	Heritage to communications & radar	MSC-1 and MSC-2 predecessors
Power Mgmt & Dist	Heavy, due to centralized WPT	Lightweight; WPT can be distributed

Area of Significant Concern

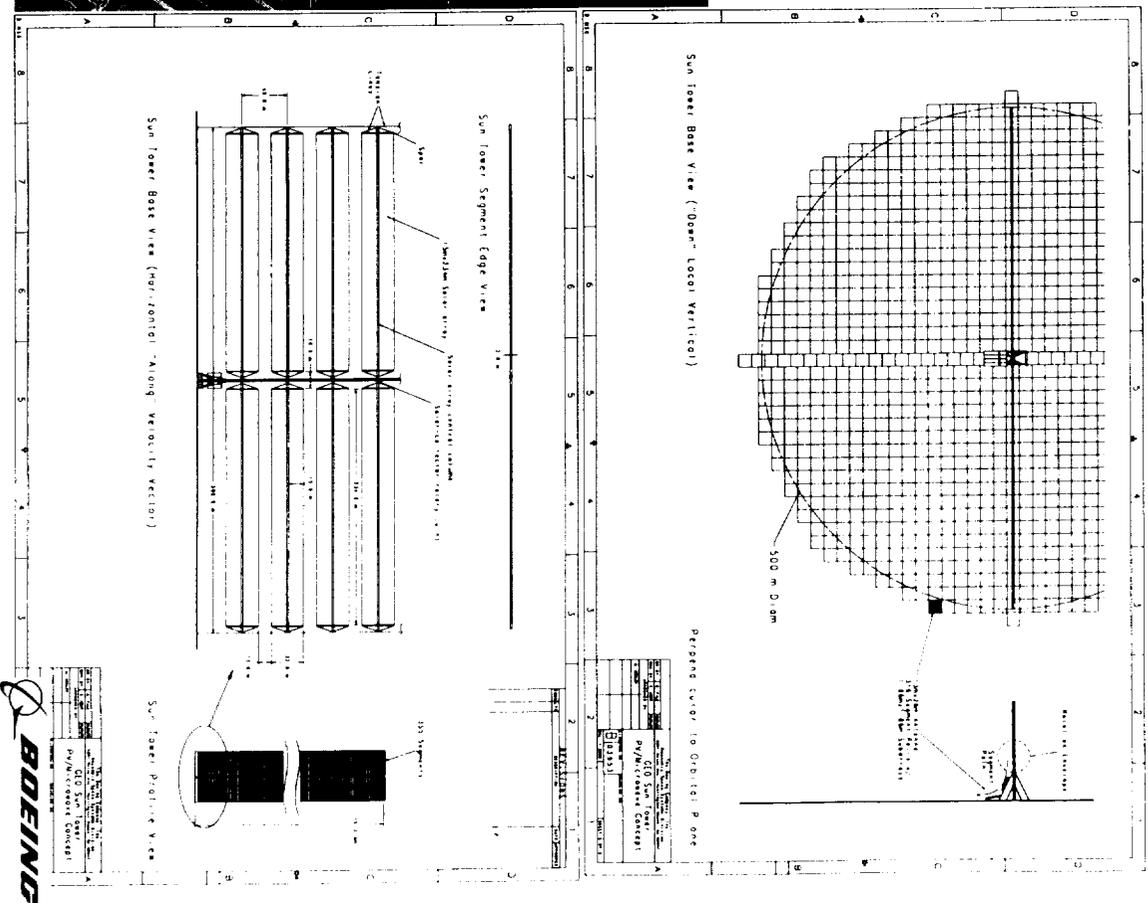
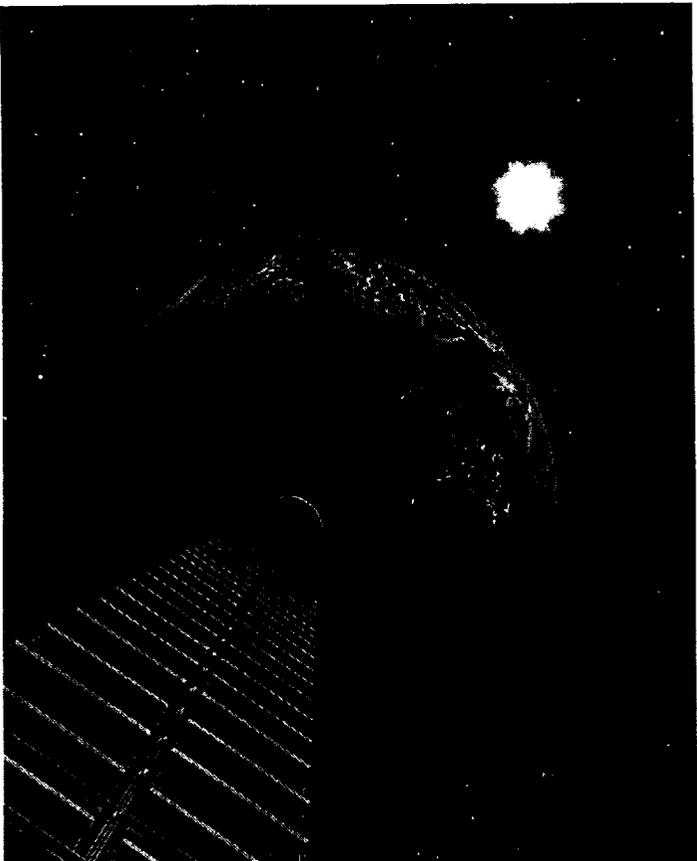
Intermediate Area

Area of Significant Benefit

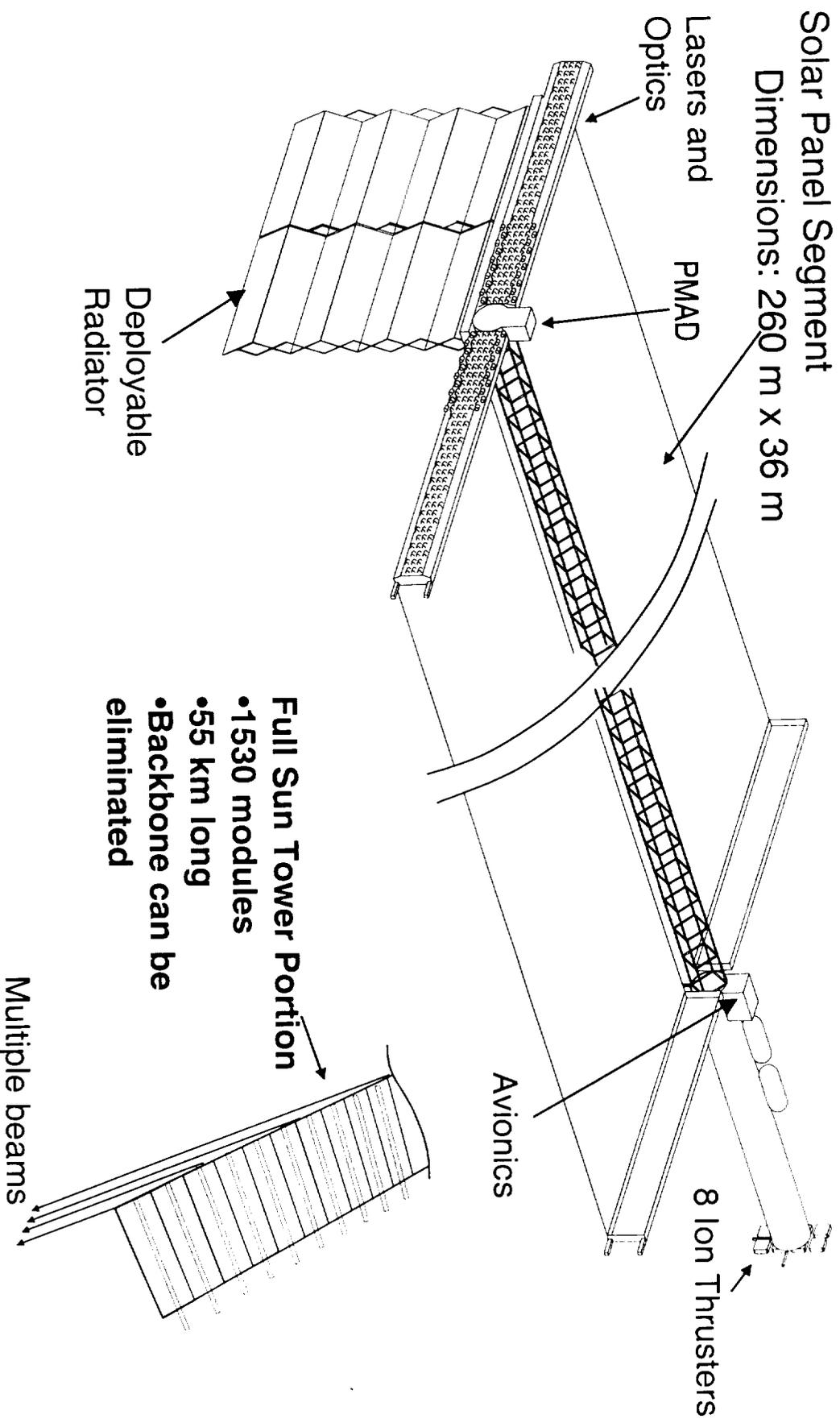


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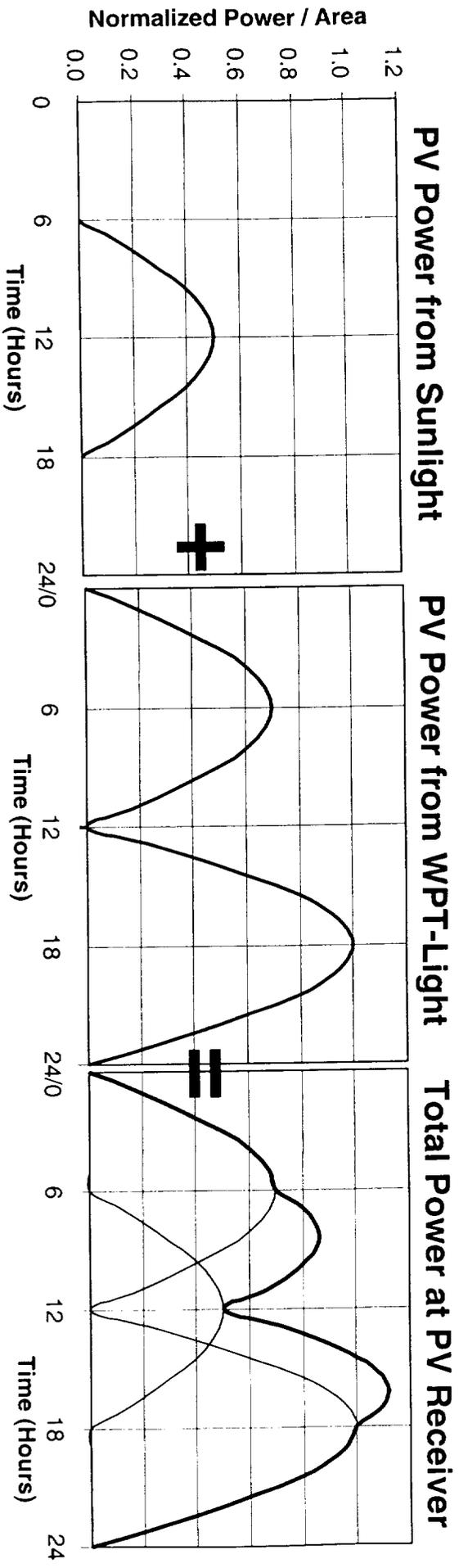


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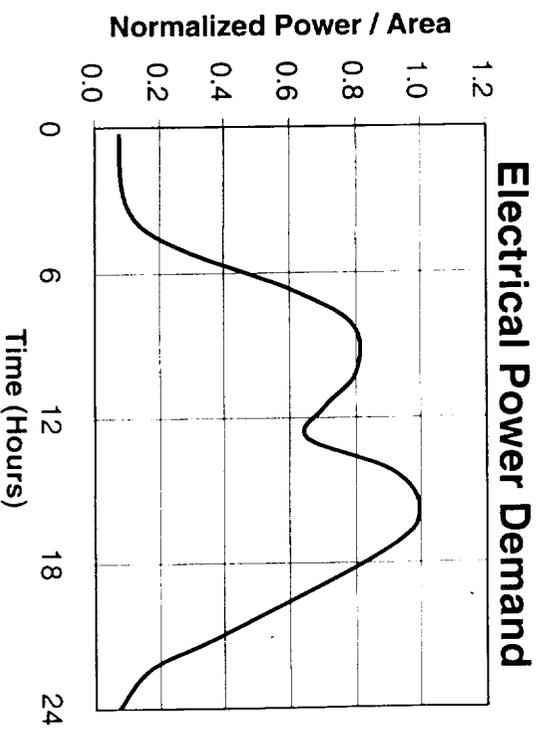
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Sunlight + Laser-PV WPT = ~ Power Requirement

Photo-Voltaic (PV) Power Station Receives Both



- Normalized Output from SPS (Non-Tracking Arrays)
- Normalized Output from Sun
- Normalized Total Output
- Typical Electricity Demand



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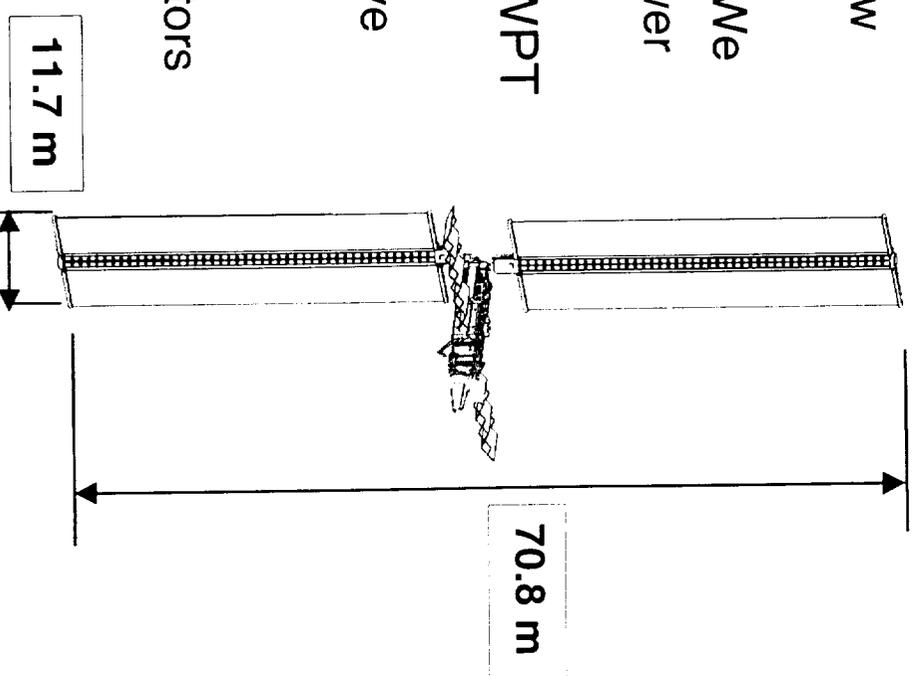
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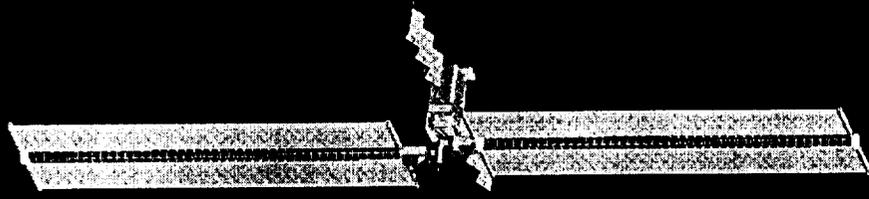
MSC-1: Near term Demonstrations

100 kW_e Power Plug Satellite

- Power System derived from existing ISS IEA (Integrated Energy Assembly)
 - IEA is successfully deployed in orbit now
 - IEA includes energy storage (batteries)
 - Current ISS array pair produces 61.5 kW_e
 - Advanced PV cells can double IEA power
 - ~120 kW_e with derivative array
- MSC-1 demonstrates solar-powered WPT
 - Efficient power generation
 - Light Emitting Diodes (LEDs) achieve >30% conversion efficiency
 - ~36 kW transmitted in light beam
 - Effective heat dissipation via IEA radiators
 - Accurate pointing of beam via reflector



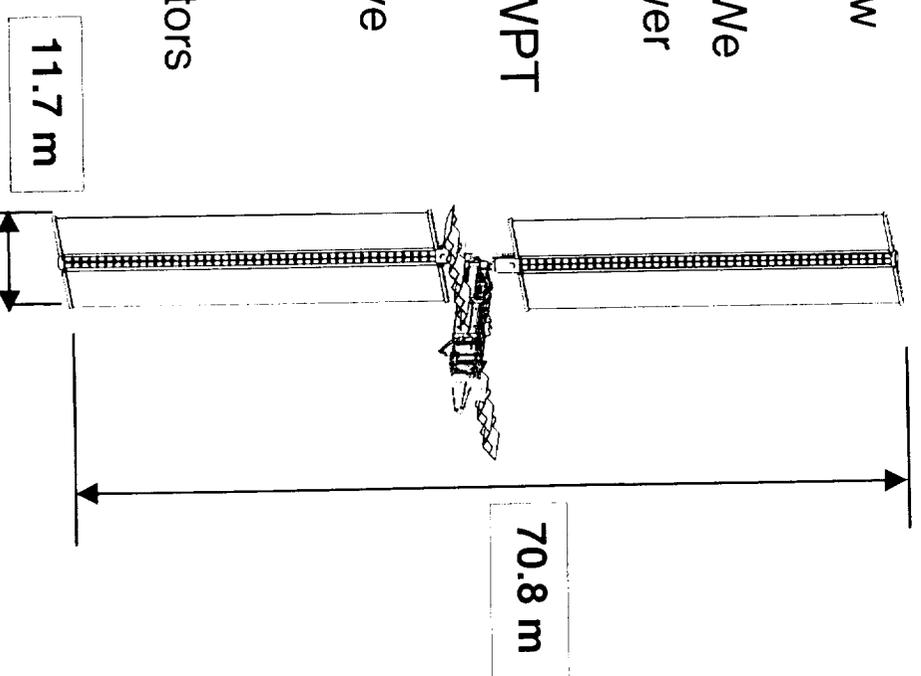


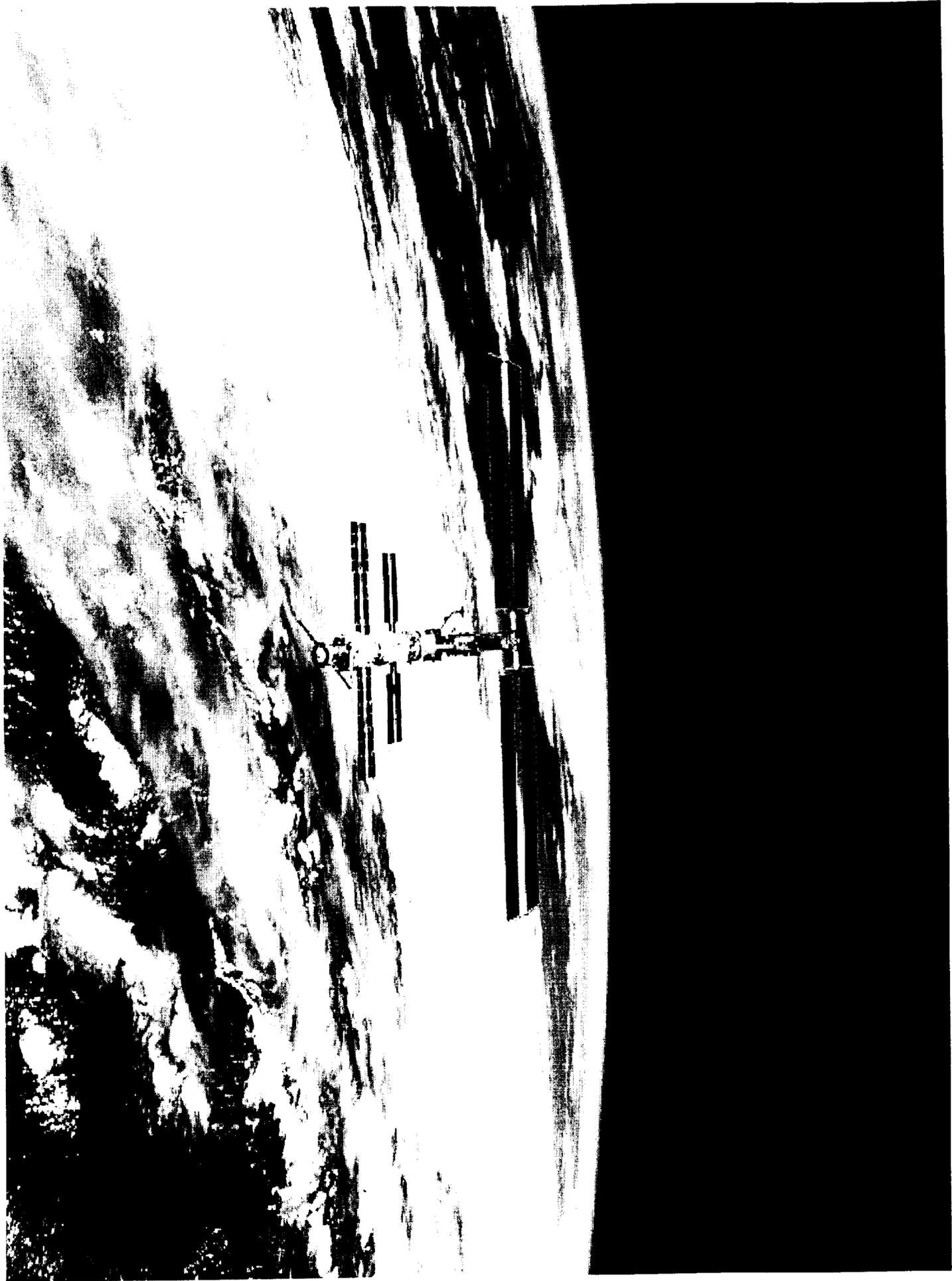


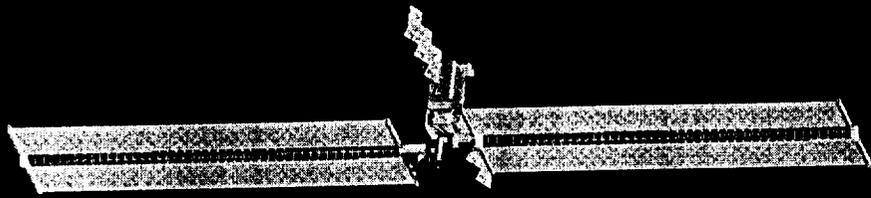
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MSC 1B: Lunar Polar Science Applications

- Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) is being developed for lunar polar applications by Boeing and NASA Marshall Space Flight Center
- A lunar polar mission could demonstrate and validate Laser-PV WPT and other SSP technologies, while enabling access to cold, permanently shadowed craters that are believed to contain ice
 - Craters may hold frozen water and other volatiles deposited over billions of years, recording prior impact events on the moon (and Earth)
 - A photo-voltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a wide range of lunar polar terrain.
- The National Research Council recently found that a mission to the moon's South Pole-Aitkin Basin has high priority for Space Science
- See paper **IAC-02-r4.04, Space Solar Power Technology Demonstration for Lunar Polar Applications**, for further details



Summary

- Farther-term micro-wave WPT options are efficient, and can beam power through clouds / light rain, but require large sizes for long distance WPT and a specialized receiver (“rectenna”).
- Nearer-term Laser-Photovoltaic WPT options are less efficient, but allow synergistic use of the same photo-voltaic receiver for both terrestrial solar power and SSP.
 - The smaller aperture size also allows smaller (lower cost) initial systems.
 - Laser-Photovoltaic WPT systems open new SSP architecture options.
 - Gravity gradient-stabilized “Sun Tower” SSP satellites may make more sense for laser systems than for microwave systems, because the receiver also converts sunlight into electricity, to correct for the cosine loss otherwise observed in power production at mid-day.
- Technology flight demonstrations can enable advanced space science and exploration in the near term.
 - “Power Plug” or “LAMP” spacecraft and Lunar Polar Solar Power outpost advance technology for far-term commercial SSP systems, while providing significant value for near-term applications.