

Wireless Power Transmission Options for Space Solar Power

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Abstract for a presentation to be given at the
International Space Development Conference
Dallas, Texas
25-28 May 2007

Space Solar Power (SSP), combined with Wireless Power Transmission (WPT), offers the far-term potential to solve major energy problems on Earth. In this presentation, 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.

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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

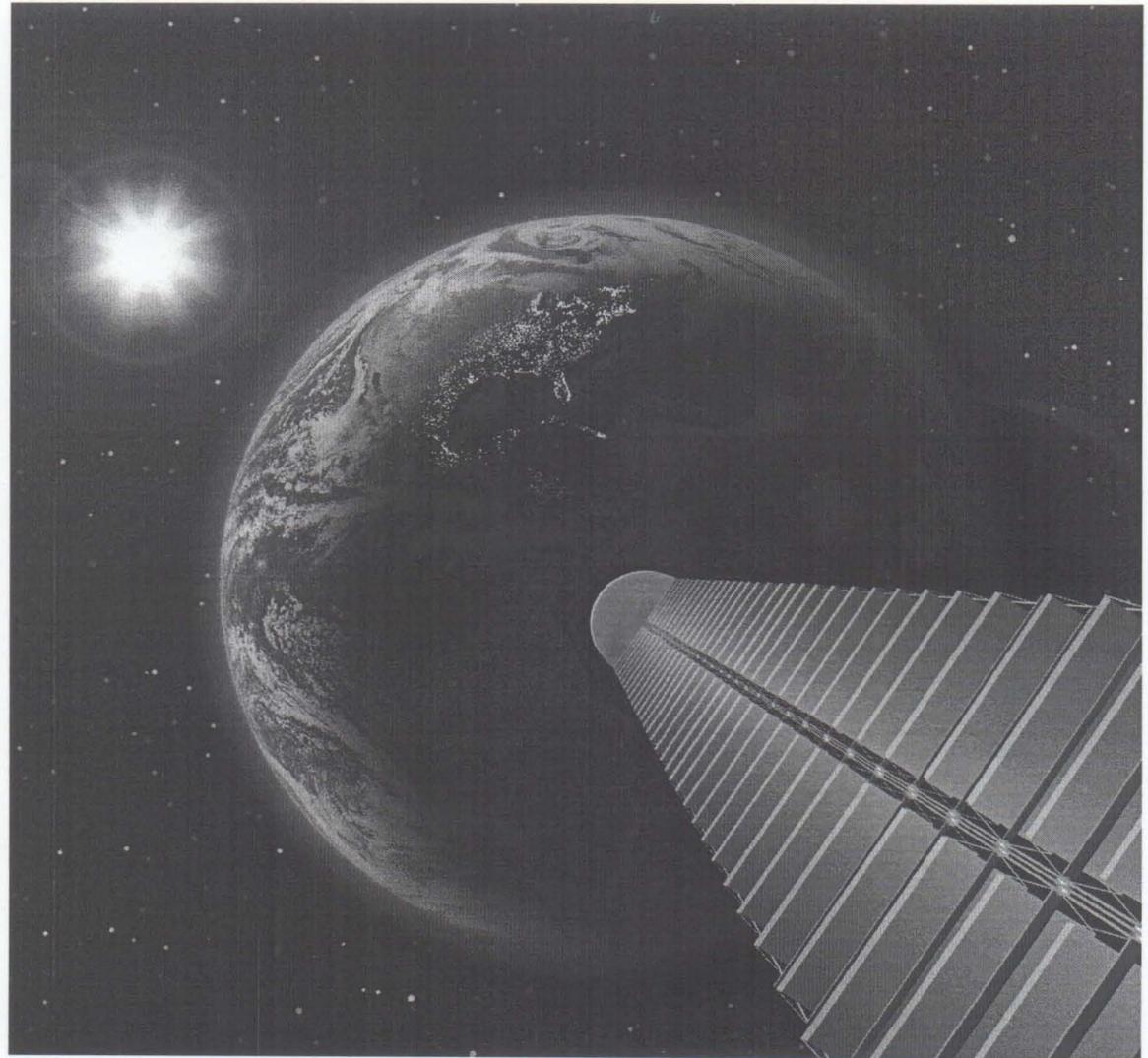
Global Power Consumption



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

- “Sun-Tower” Design based on NASA Fresh Look Study
- Transmitter Diameter: 500 meters
- Vertical “Backbone” Length: 15.3 km (gravity gradient)
- Identical Satellite Elements: 355 segments (solar arrays)
- Autonomous Segment Ops:
 - 1) Solar Electric Propulsion from Low Earth Orbit
 - 2) System Assembly in Geostationary orbit
- Large Rectenna Receivers: Power production on Earth



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

Solar Panel Segment
Dimensions: 260 m x 36 m

Lasers and
Optics

PMAD

8 Ion Thrusters

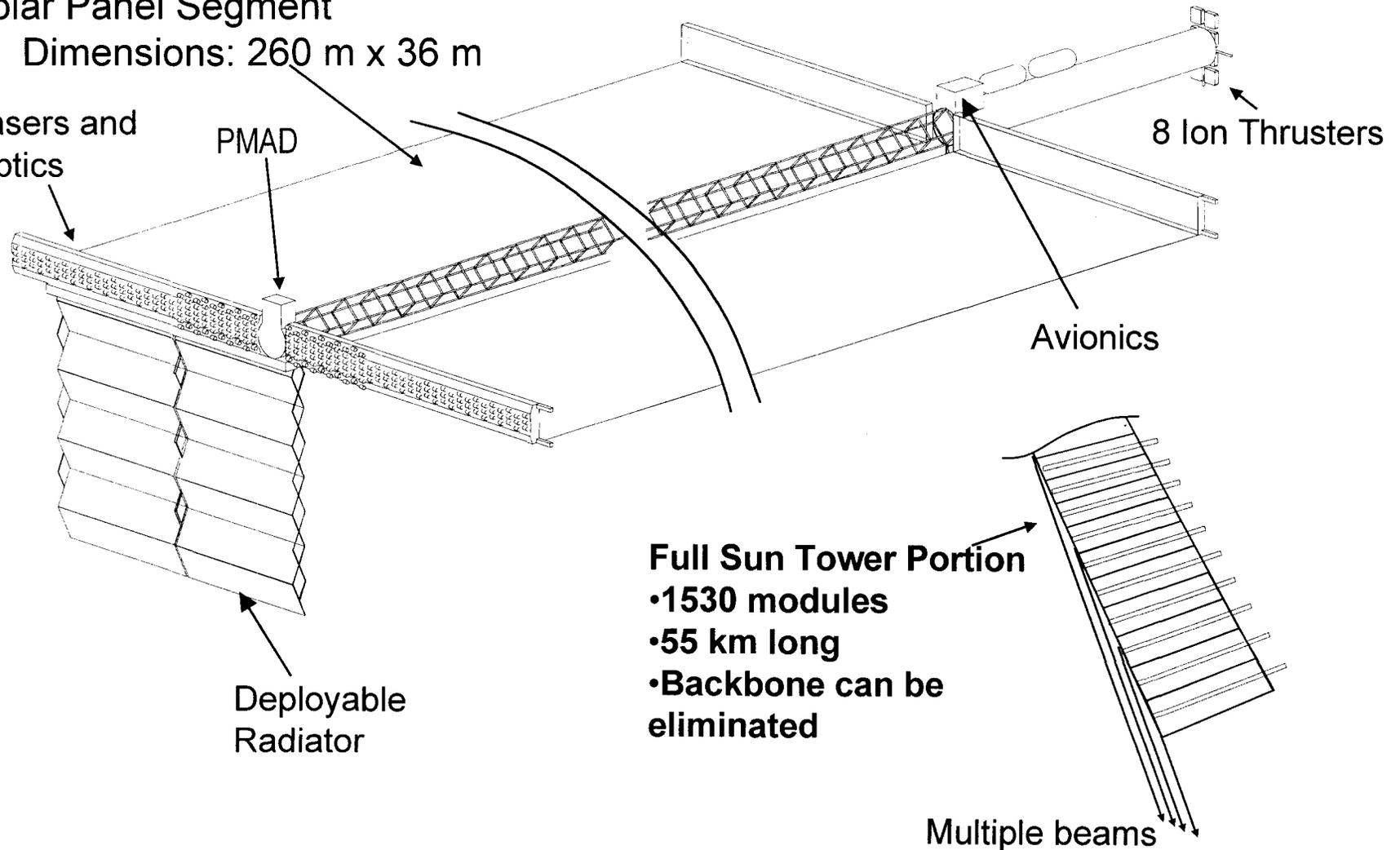
Avionics

Deployable
Radiator

Full Sun Tower Portion

- 1530 modules
- 55 km long
- Backbone can be eliminated

Multiple beams

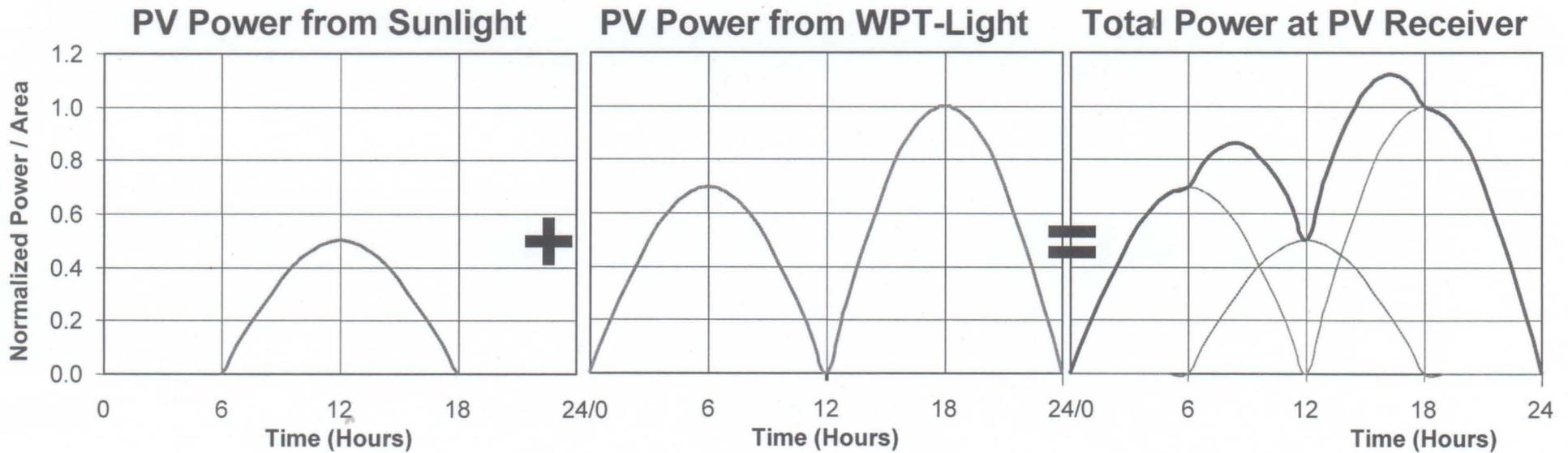


Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

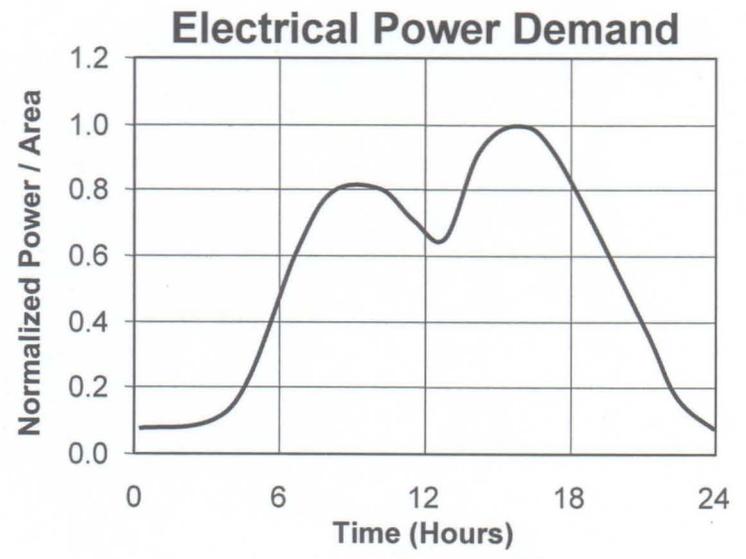
- Large photo-voltaic (PV) power plants in Earth's major deserts (Mojave, Sahara, Gobi, etc.) receive & convert light from 2 sources:
 - 1) Directly from the Sun, and
 - 2) Via WPT from SSP systems
- Laser light is transmitted and converted more efficiently than sun-light
 - Wavelength is selected for good atmospheric transmissivity
 - Efficient Light Emitting Diode wavelengths match common PV band-gaps
- Gravity gradient-stabilized SPSs 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



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



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, NTA, 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



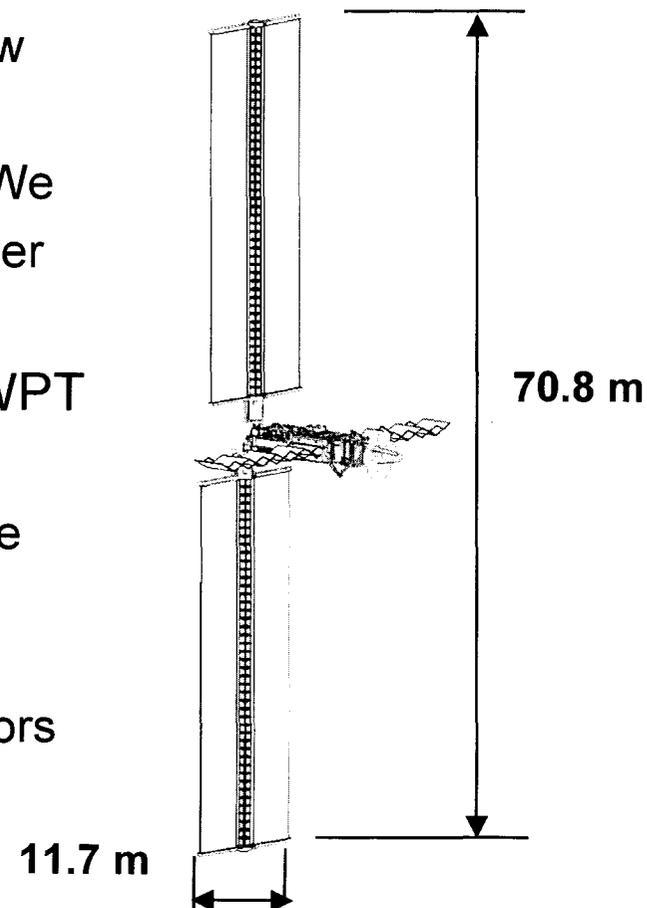
Area of Significant Concern

Intermediate Area

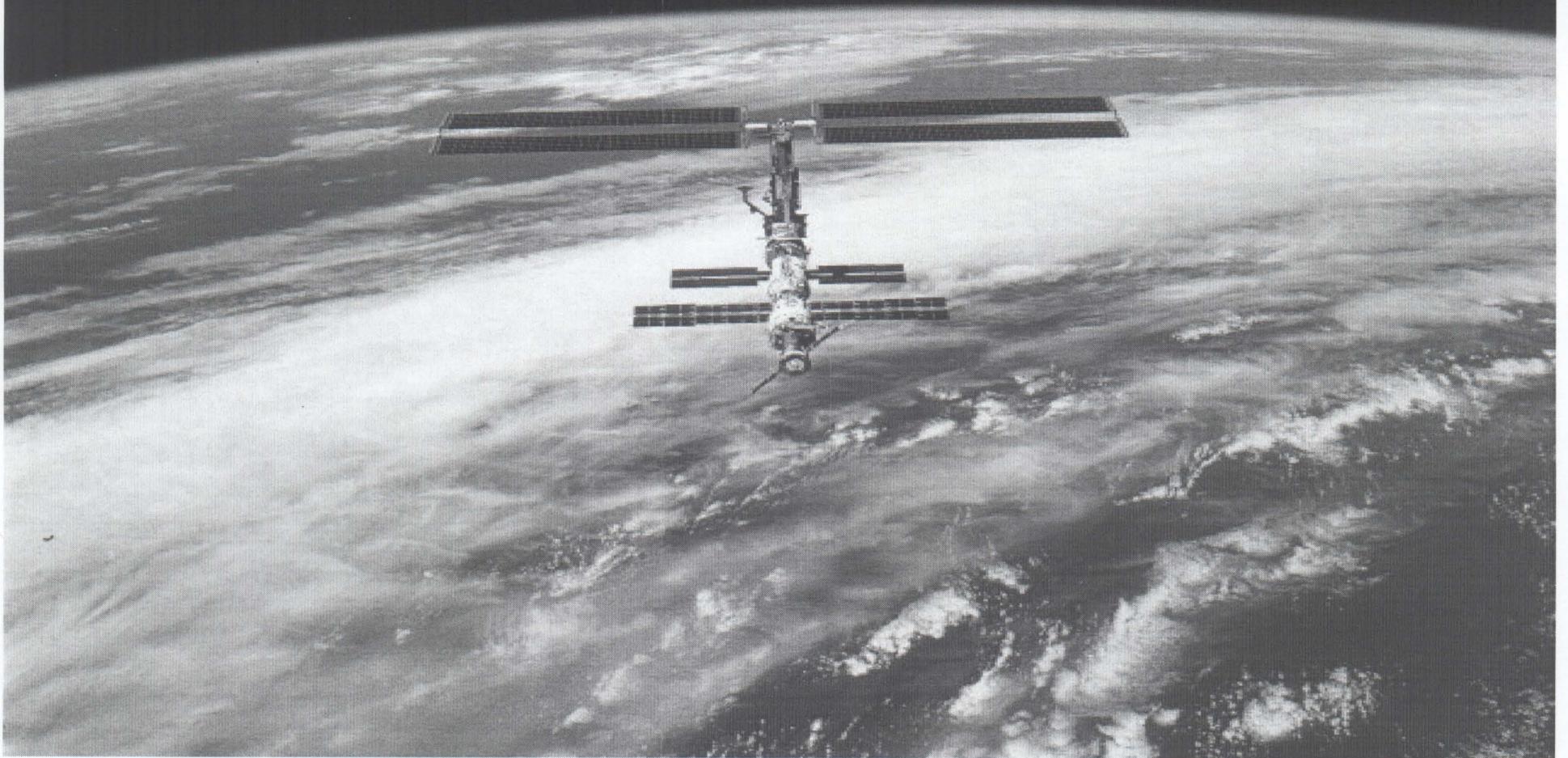
Area of Significant Benefit

MSC-1A: Near Term Demonstration 100 kWe Power Plug Satellite

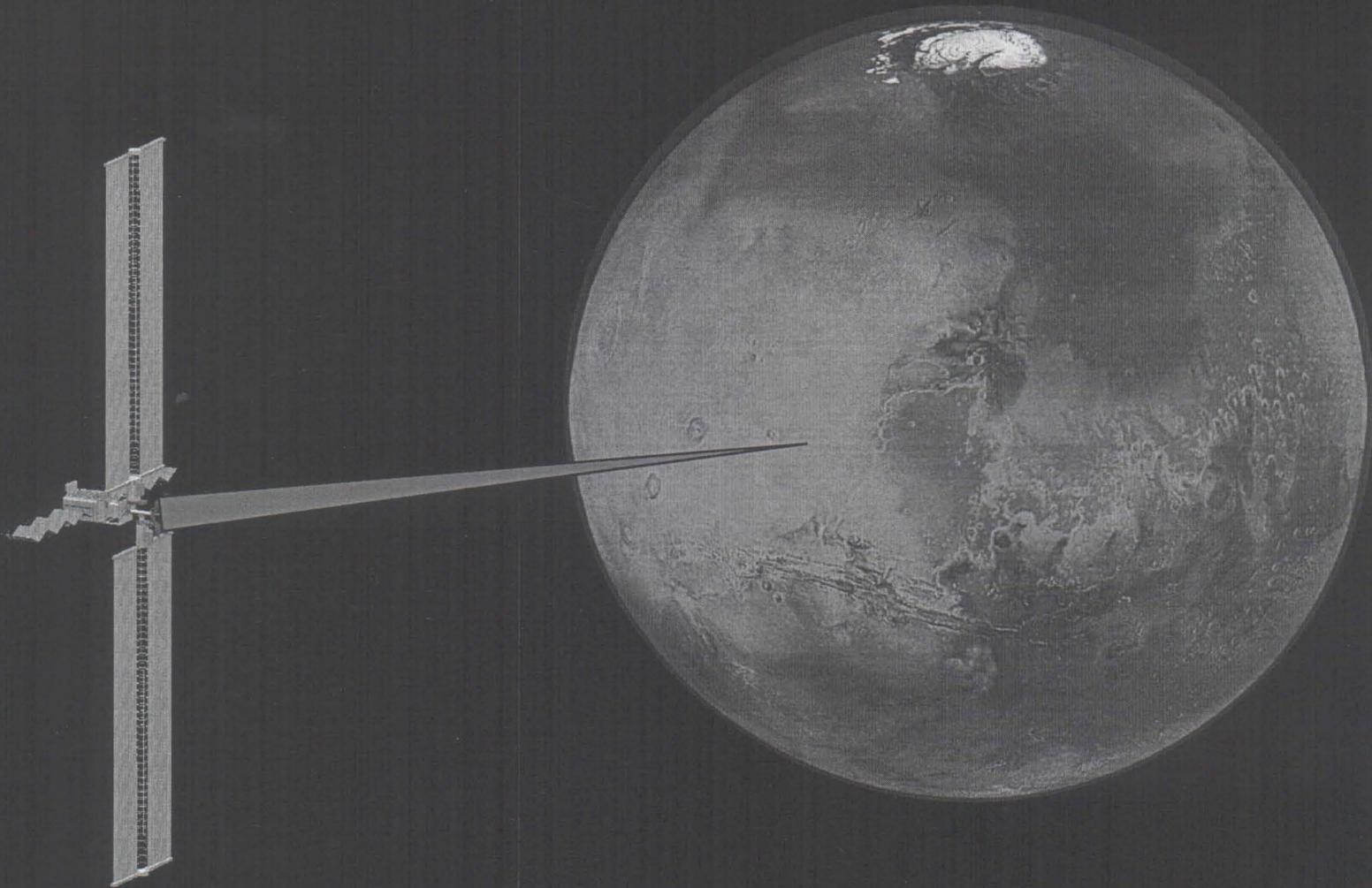
- Power System derived from existing ISS IEA (Integrated Energy Assembly)
 - IEA is successfully deployed in orbit now
 - IEA includes energy storage (batteries)
 - Current ISS array pair produces 61.5 kWe
 - Advanced PV cells can double IEA power
 - ~120 kWe with derivative array
- MSC-1 demonstrates 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



ISS with IEA Solar Panels Fully Deployed
Current flight experience with large IEA reduces risk for
near-term derivative applications



MSC-1A: Lunar and Mars Power (LAMP) Application Laser WPT to Photo-Voltaics on the moon or Mars



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 (& Earth)
 - A photo-voltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a large area of polar terrain
- The National Research Council recently found that a mission to the moon's South Pole-Aitkin Basin should be a high priority for Space Science
- See paper **IAC-02-r4.04, Space Solar Power Technology Demonstration for Lunar Polar Applications**, for further details

North Pole (SEE BELOW)

Moon's Orbit

Sun Rays are Horizontal
at North & South Poles
•NEVER shine into Craters
•ALWAYS shine on Mountain

South Pole (SEE BELOW)

Direct
Communication
Link

Solar Power
Generation on
Mountaintop

Wireless Power
Transmission
for Rover Operations
in Shadowed Craters

Space Solar Power Technology Demonstration For Lunar Polar Applications

POSSIBLE ICE DEPOSITS

- Craters are COLD: -300F (-200C)
- Frost/Snow after Lunar Impacts
- Good for Future Human Uses
- Good for Rocket Propellants

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 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.