

Wireless Power Transmission Experiment using an airship as relay system and a moveable rover as ground target for later planetary exploration missions

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Abstract

The Wireless Power Transmission (WPT) technology has been treated to a wide extent in the recent years. A broad variety of applications has been investigated, from earth to orbit, orbit to earth, in-orbit and planetary ones, as for moon and Mars missions. In this course the question to use laser or microwave technology has widely been discussed. Beaming energy to spacecrafts could provide an important space mission-economic potential. It promises significant reduction in the cost of access to space, for scientific and commercial missions, and increases the mission capabilities for in-space systems. For the future enhancement of ISS capabilities and operational efficiency, the use of WPT technology became part of the technology research planning for the ISS. The WPT may have the potential of providing operational benefits, increase of spacecraft systems efficiency for elements like co-orbiting platforms, transfer vehicles or other ISS related in-orbit spacecrafts, and planetary exploration vehicles. The laser technology provides specific technical, operational and economic benefits compared to microwave applications and provides the actual basis for the envisioned wireless power transmission concepts. An outlook in terms of future wireless power perspectives, both for terrestrial as for space-to-space scenarios is given; these applications are part of a technology demonstration roadmap for wireless power transmission key- and supporting technologies, which is characterized by dedicated technology demonstration milestones on ground and in space. The actual technology development philosophy as conceived at EADS-Space Transportation is described and includes main system demonstration missions, as a laboratory test bed employing a small rover system, a scaled airship model demonstration as planned in 2004 and an experiment onboard the International Space Station ISS. These demonstrations represent milestones in terms of technical capability verification on the way to solar power platforms in space, as an actual Solar Power Platform Design Concept in the 400 kW range for GEO including the receiver side on ground. Special attention is given to the fact, that technological spin-offs out of the Solar Power Platforms development are an essential aspect of the activities.

The application of the suitable type of laser systems for future solar power concepts in space will be discussed, based on recent investigations in the frame of the EADS technology development work.

The experimental application of a laser system for power transmission to a moveable and steerable target, a small rover, is addressed also and the demonstration philosophy and experimental set-up are detailed. The ground test objectives, the definition, design and performance of a "Wireless Power Transmission" system and the demonstration of the basic principles of power transmission and target acquisition, pointing and tracking are covered. The lessons learned and consequences for a continuation of this type of demonstration are outlined.

Introduction

The Space Power Infrastructure (SPI) project at EADS-SPACE Transportation (EADS-ST) aims at a commercial application of 'Power from Space' in the long term, embedded in an international economical, political and legal network. The EADS-ST wireless power ground experiment is a BEOS funded project and part of the general SPI company strategic initiative.

The project requires investigations in non-company key technologies, like laser, as design

driving factors are essential, as basis for the work on the space systems itself.

Taking a look on the Solar Power systems implementation approach, probably SPI systems in the near term has to be envisaged as public funded projects (ESA, DLR, EU, UNO, World Bank, e.a.), where as the identification of earlier, mid-term and other, promising 'niche markets' seems to be feasible.

The EADS-ST company key interests related to SPI as potential future strategy, are in the fields of space transportation (ETO, Orbit-Orbit), like

- space infrastructure
- space propulsion
- space operations

The major topics of conceptual work of the EADS-ST company initiative are the identification and quantification of medium/long-term customer markets and so called market niches or applications for the intermediate timeframe, the identification of future SPI-scenarios as long-term perspective based on Company Global Solar Energy Concept („GSEK“), the establishment of a roadmap as implementation strategy („step-wise approach“) with intermediate milestone missions serving as actual decision platforms for the further proceeding and the definition of a SPI-infrastructure in orbit (GEO & LEO) and on ground and concentration on functional key-systems in the roadmap as „intermediate“ elements:

- *GND-Demonstrations*
- *ISS-Experiment*
- *LEO/GEO-Demonstrators*
- *GEO Pilot Platform*
- *Investigations in the alternative Moon-based power scenario*

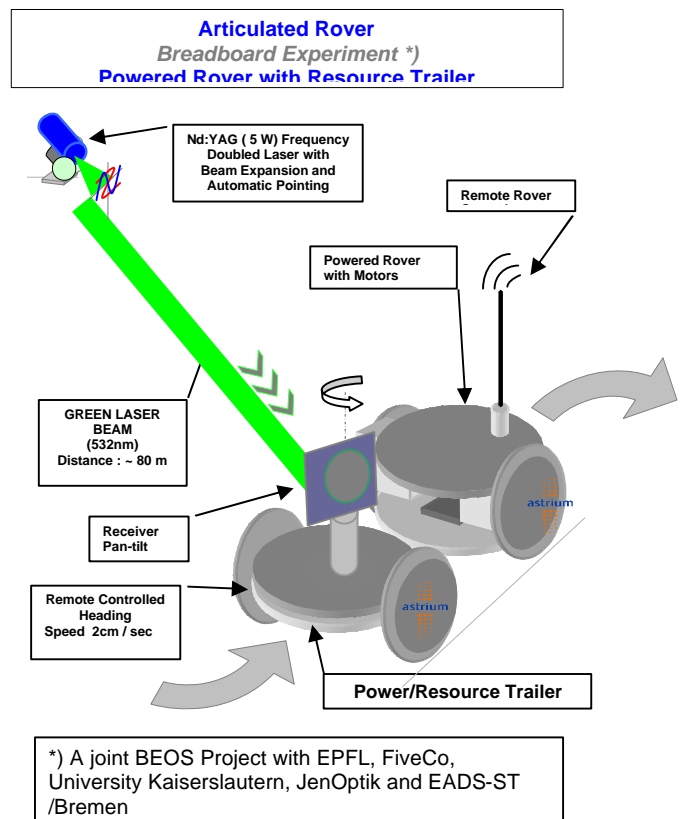
The rover experiment as ground demonstration is an early contribution in that line of technology demonstrators, and is to be understood as demonstration of enabling basic functional capabilities for future in-space and planetary systems. The application perspectives for this experiment are space technology and science platforms, ISS applications and planetary vehicles, like manned and robotic exploration rovers. These potential target mission scenarios encompass scientific or technology missions to lunar or Martian remote regions with restrictions on the systems power supply (e.g. mission duration, non-scheduled extension, unfavourable sunlight conditions, outside temperature).

Purpose and Experiment Description

The experiment should demonstrate the feasibility of a complete wireless power transmission link between a laser transmitter and a distant receiver system. The laser transmitter system is capable of automatically find and identify the target, point at it and keeps it and tracks it, as the target is a moveable small rover.

The rover itself as receiving system is equipped with a laser beam receiver system, which adjust

itself automatically to the incoming laser beam. The rover is a micro-processor controlled system, equipped with a micro-colour camera. It is remotely control via a PC operator interface. The laser beam energy feeds all rover electrical systems, the micro-motors, the micro-camera, the micro-processor and the video transmitter unit. The transmission distance is feasible between 30 and 200 m. The sketch below illustrates the principal experiment set-up.



For the laser, a frequency doubled Nd:YAG solid state laser at 532 nm by JENOPTIC was used, with an output power of 5 Watts. The beam diameter is expanded up to 30 – 50 mm. The choice of frequency doubling was done due to demonstration reasons (visible green laser light) and safety reasons. For further experiments the original wavelength of 1064 nm would be chosen (non-visible infrared light).

The rover used is a micro-processor control vehicle by the company FiveCo and the EPFL, Lausanne / Switzerland. The specific properties are its low energy consumption, easy speed control and the integrated micro-camera. The rover dimensions are 240 mm length, 120 mm width and the max. speed is about 5,5 cm/sec, with a max. half turn radius of 240 mm. The vehicle has a total mass of 230g and is equipped with four DC electro motors, a 433

MHz radio-link for the reception of the control commands, a digital camera with 2,46 GHz transmitter and super-caps for a 13 seconds power supply.

A rough energy budget is as follows:

- electronic LED's (standby modus) ca. 70 mW
- radio-link ca. 150 mW
- motors ca. 120 mW
- camera ca. 600 mW
- total power ca. 1000 mW

The rover requires a power supply with a voltage of 6V. This results in an efficiency requirement of energy conversion of min. 20% for the camera operation. The rover is remotely controlled via a radio link and a PC interface. The camera pictures are transmitted to the receiver unit, which feeds a TV screen. The transmission distance for an outside link is about 75 m in the moment, and for inside transmission ca. 40 m (it strongly depends on the environment). In the figures 1a) and 1b), the rover in its original status, without the receiving panel is depicted.

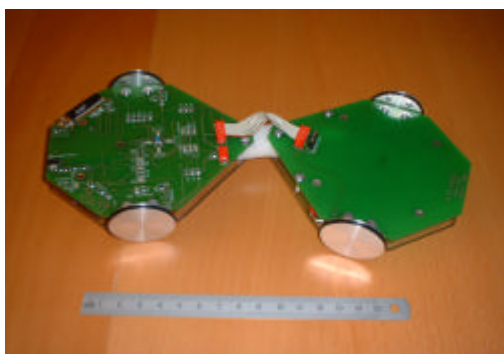
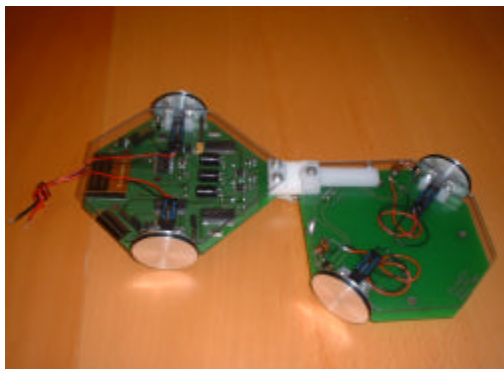


Figure 1a and 1b: The Micro-Rover System from FiveCo, Upper Side (Right) and Bottom (Left)

For the experiment set-up a few principal issues had to be solved, for example, concerning the control of the laser beam steering, what kind of

information and where it does come from is needed for the laser transmitter unit. For the spatial control of the laser beam, two axis degree of freedom are needed, the rotation about the horizontal and vertical axes. The laser beam initially is being displaced by a set of independent mirrors for each axis. Thus, several levels of beam control are being implemented. The control levels could be addressed via a digital I/O-card by the computer. In the Figure 2 the main functional elements are depicted.

The Fig. 2 does not show the laser beam expansion optics for the 30 mm final beam diameter.

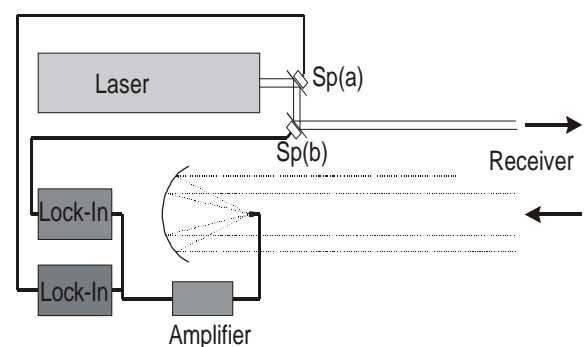


Figure 2: Functional Elements of the Transmitter

For the identification of the target system (rover) position the retro-reflections of the laser beam are used. For the generation of this type of identification signal, a retro-reflection foil at the rover receiver panel is applied. Whereas the most part of the laser light is being absorbed by the photovoltaic cells and converted into electricity, only a small portion of it can be reflected; the reflection foil is placed concentrically around the PV-cells, as shown by the Figure 3.

The computer control programme principally starts with a scan modus scanning line-by-line the target area. After having identified the target, the laser beam is pointed at the centre of the PV cells.

The generated signal is converted into a certain voltage by a photodiode, which is received by the I/O-card of the control computer and identified. For increasing the signal intensity an interference filter element for green light is positioned in front of the diode, and additionally a Schmidt-Cassegrain-type-telescope assembly is applied (look figure 2).

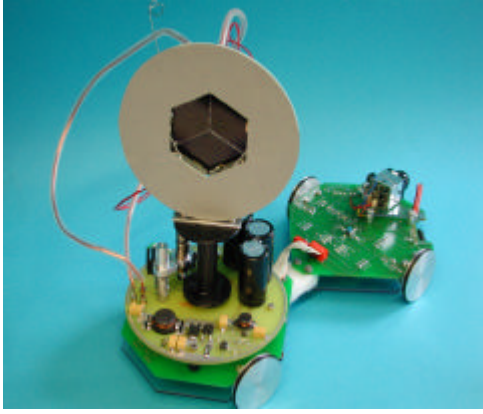


Figure 3.:The Micro-Rover with Receiver Panel

The diameter of the reflector mirror is 500 mm. For insuring a continuous rectangular positioning to the reflected light, the aperture follows the beam.

The rover receiver system converts the laser light into DC current by photovoltaic cells and transforms it to 6 V. A further aspect is the requirement, that the PV/Retro-Foil Panel is pointed automatically perpendicular to the incoming laser beam. For enabling this, the panel is rotated by a small motor.

The photovoltaic cells for the receiver panel are a dedicated fabrication from the company RWE Schott Solar. Due to efficiency reasons, and thus regarding the semiconductor material and laser light frequency, GaInP (Bandgap 1,85 eV) photovoltaic cells has been selected. The design of the PV receiver is optimized w.r.t. the Gaussian laser beam profile.

In the Figure 4 the local distribution of the power density optimal for the PV cells is depicted.

For the PV receiver panel a hexagonal shape was taken and, in order to easily to exchange defect cells the area is composed of three separate cells. A single PV cell has a length of 25 mm each edge.

In order to prove the power capability of the photocells, the power level to voltage characteristics has been monitored, which is shown by the Figure 5.

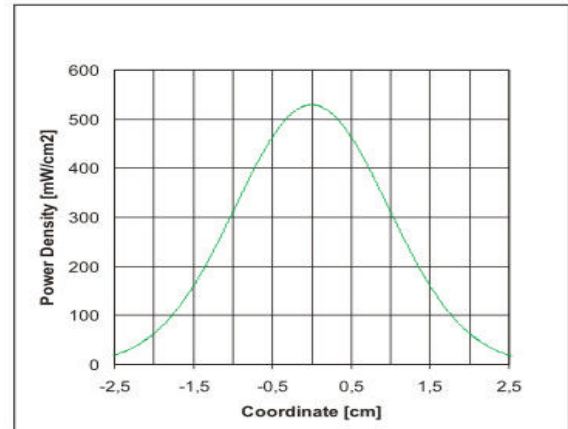


Figure 4: PV Cell Optimized Power Distribution

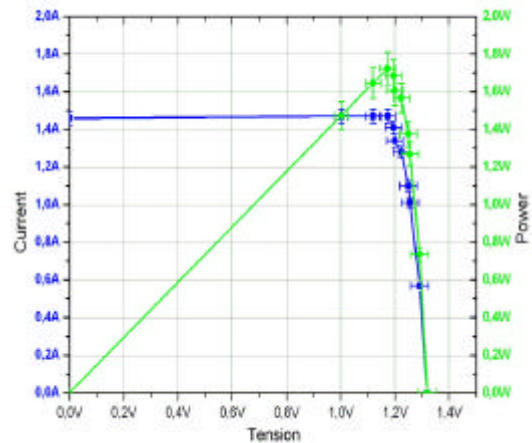


Figure 5: Power to Voltage Characteristic at 4,3 Watts

The characteristic has been measured at 4,3 Watts green laser light. The operational point is at 1,15V, with a current power of 1.5 Ampere, a performance of 1.75 Watts and an efficiency of about 40 %. As a result from these measurements, it could be stated a sufficient level for powering the rover systems.

In the following Figure 6 the main elements of the power transmission system are shown.

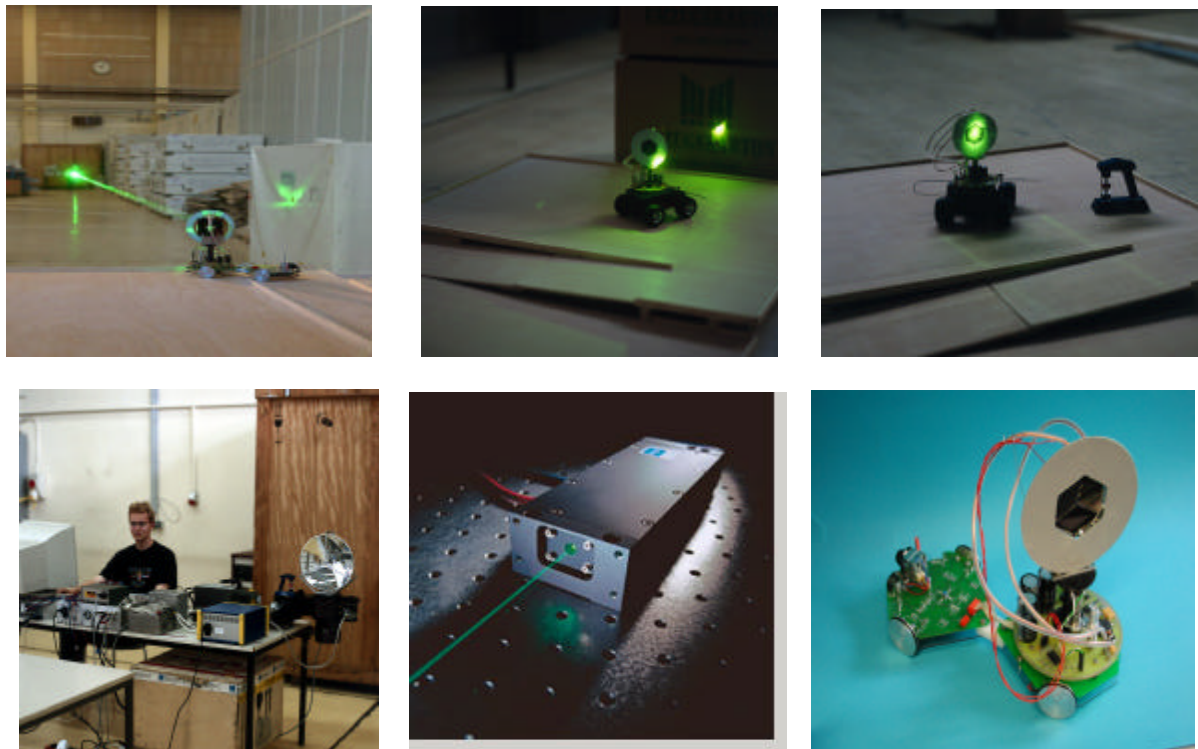


Figure 6: Main Elements of Power Transmission System (Complete Transmission Chain, Laser Acquiring the receiver Panel centre, Laser Beam Pointed at Receiver Centre, Laser Transmission Unit with Detector Mirror, Nd:YAG Laser from JenOptik, Micro-Rover Assembly from EPFL/FiveCo and Receiver Panel from University Kaiserslautern; sequence from top left to bottom right)

Outlook on Future Activities

The rover demonstration is an early distribution as one element in a technology development roadmap, which foresees certain key-milestones, as ground experiments, and demonstrations in space.

There are a feasibility technology WPT demonstration from onboard the ISS, providing a complete power transmission chain from orbit to ground, a 500 kW space demonstration power platform in Low Earth Orbit and Geostationary Orbit, and 1 MW to 1 GW power pilot facilities in the geostationary orbit.

The demonstration approach is aimed at space applications, involving free-flying platforms (ultra-micro g crystal growth) and the ISS, and planetary exploration vehicle in space or on the planets surface.

Each of the demonstration milestones provides a point of decision in the frame of the actual programmatic, political and technological circumstances for the following key-technology development activities and the technology demonstration missions planning.

A next following step for the rover experiment would be,

- increase of power level
- increase of transmission distance
- increase of laser pointing accuracy / stability
- implementation of data transmission capability

In the following Figure 7 the general SPI technology roadmap is depicted, addressing key-technology demonstration milestones on ground and in space, and the related accompanying programmes, as launcher systems and ground infrastructure elements.

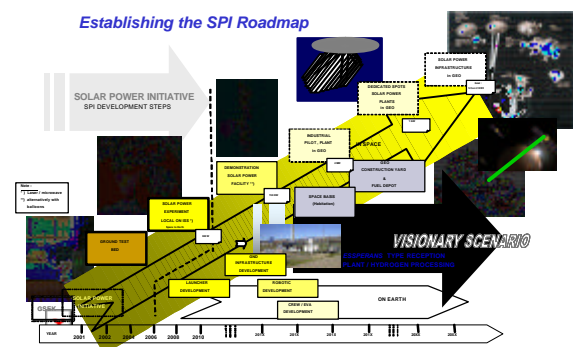


Figure 7: SPI Technology Development Roadmap

The lessons learned out of that breadboard activities concern a set of different experiences made. These are the following in principle:

- light intensity and stray-light influences and related compensation required
- air disturbance influences a need to be compensated
- laser beam control accuracy and speed to be improved
- resistance against disruption of laser beam
- laser beam forming to be improved

WPT Chain Breadboard Continuation

The enhanced laser power transmission chain test set-up shall improve the power supply to remote vehicles, the control of the laser beam, the distance and the complexity of a self-controlled power supply system, involving two independent vehicles. It uses the same rover system as described, but involves a 6 DOF airship as relay station. The airship has a selfstanding onboard laser beam control and steering system to supply the ground rover with power. At the same time the airship onboard system are feeded with energy by the laser beam. In the Figure 8 the experiment configuration is shown, with the laser system, the airship and the ground rover, as final target system.

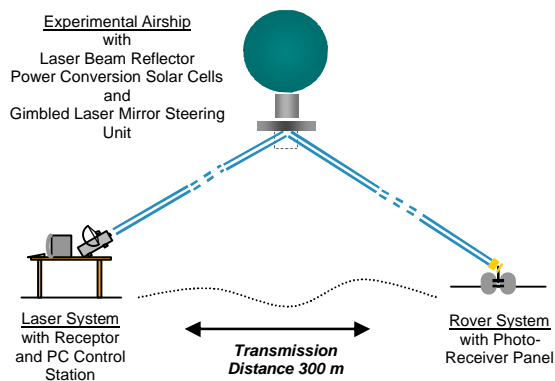


Figure 8: Laser Power Transmission Set-Up

The demonstration will consist of a laser transmitter station unit, a relay air-based system and a ground receiver unit which should be mechanically and electrically entirely independently of each other, the only connection between them is the laser beam.

The transmitting station consists of the beam source (laser), the beam shaping optics, beam distraction in two directions, control electronics

for the beam distraction, to a detector for the light reflected by the relay system with amplifier, a control for the target acquisition and a beam tracking control. The power supply for all devices is integrated in the transmitter station.

The relay station consists of a platform freely mobile in 6 degrees of freedom with a functionally coupled receiver and transmitter unit. This unit provides the retro-reflector necessary for the beam tracking, a control system of the adjustment of the receiver's panel on the incident beam and a converter for the conversion of the beam power into electricity for the supply of the airship subsystems.

In the transmitter unit the incident beam is transformed so that by means of a beam forming optics, beam distraction can be supplied in two directions, and the power electronics for the beam distraction, the detector for the light reflected by the receiver's unit with amplifier, a control for the target acquisition and a beam tracking control of the receiver's unit are supplied with energy.

In the receiver unit are integrated the retro-reflector necessary for the beam tracking, a control system of the adjustment of the receiver panel to the incident beam and a converter for the conversion of the beam power into electric energy for supply of the ground vehicles subsystems. The receiver unit is designed for assembly on the remote controlled ground vehicle.

EADS Concept for an ISS Demonstration Experiment

The demonstration of a closed laser power transmission chain from space to ground is the purpose of this concept. On-board the ISS and attached to one of the external Columbus payload facilities the laser transmitter and control system is accommodated. The ground reception site is located along the ground track of the station. The same principles as for the previous breadboards shall be applied, but improved and adapted to this application. So, a self-controlled laser beam target finding and acquisition system at the ISS and a self-controlled ground receiver and ISS laser source following receptor facility are used. The use of both, a low power pilot laser for target acquisition and a power laser are being conceived. The power level should be in a range to demonstrate the feasibility of the

concept. In the Figure 9 the laser system mated to an ISS external facility is shown.

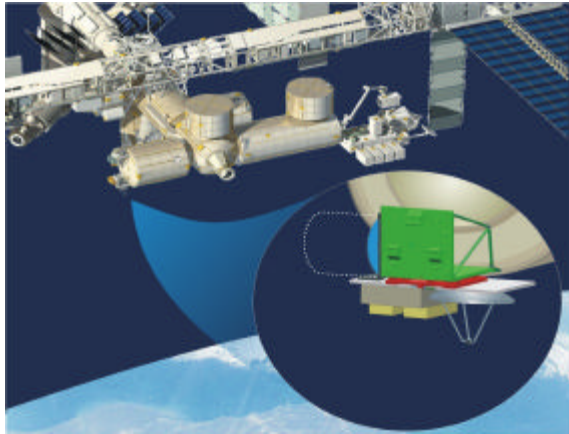


Figure 9: ISS-based Laser System

The ISS-based system has a mass of about 250 Kg, a power level of 300 W, a Diode/Nd:YAG laser type and a ground reception area of 500 m diameter (according to the beam divergence) consisting of individual receiver elements. The laser optics have 50 mm diameter and 3000 x 200 mm shape. It uses 1 W single units and 300 units in total. the primary power demand is 1500 W. Alternatively a Nd.YAG laser with 10 W single sticks and diode pumped could be taken, with a primary power of 3500 W. The system has a 2 axis control of in-orbit transmitter optics (or stacked diodes units) and 2 axis control of ground receiver panels in a closed loop with a compensation of ISS structure dynamical disturbances.

The mission duration is planned 6 months with separate experiment cycles. The thermal control provides a radiator of 100 W capacity average.

The system uses ISS back-up control, the data handling system, GND processing and the data link to the ISS, with the initialisation of system operation. The experiment equipment could be launched by the STS or Progress and requires the ISS robotics for assembly.

EADS Concept for a GEO Demonstration SPS Platform

The SPS platform as demonstrator in GEO provides a power level of 400 kW output in space and a size of approximately 400 m in diameter. It shall be launched by an Ariane launcher and is self-deployable without any external help.

The SPS concept consists of a solar light reflector and a receiver unit. The reflector has to be permanently pointed towards the sun, and the reflector unit incorporates the photovoltaic cells, additional sunlight reflection mirrors in order to enhance the sunlight intensity to the PV cells by the factor of two.

Furthermore, the radiators are located at the bottom side of the platform. The solar reflector unit is launched into LEO and is spiralled up to GEO by its own electric propulsion system. Both systems have electric attitude control systems, which are supplied by the PV power system. Both units are not linked together mechanically, this shall be a co-orbiting, in formation flying system. The key-principle of this concept is to reduce the thermal control problem by expanding the lasers as heat sources over the receiver plane and gives each laser unit its own thermal radiator.

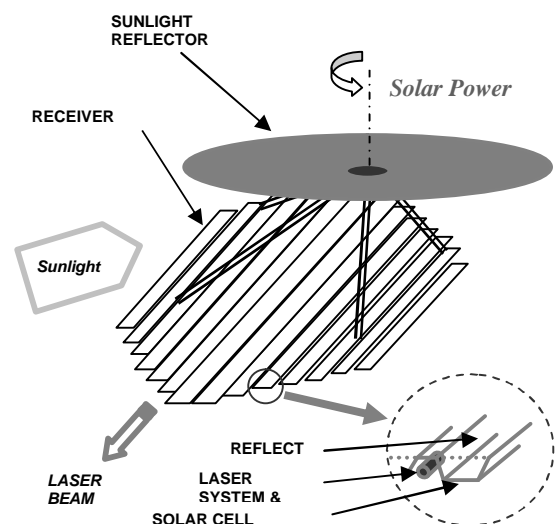


Figure 10: SPS Demonstrator for 400 kW

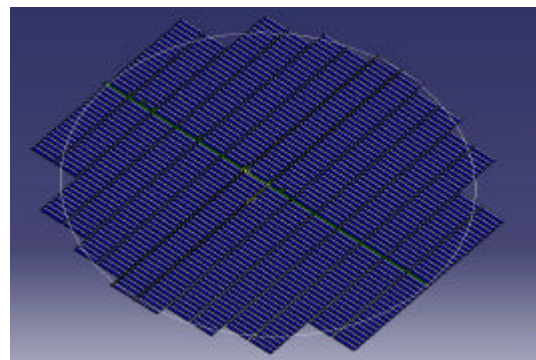


Figure 11: SPS Platform Configuration

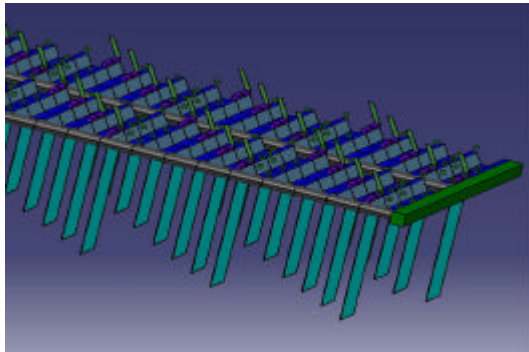


Figure 12: SPS Platform Inflatable Subunit with Laser and Radiators

Option for a Solar Power Supply European Concept

The typical system development paths are depicted in the Figure 13 below, first starting with the terrestrial PV power facility, then combining the same facility with power from space, when the orbital segments are established; there starting with one facility, followed by a second in space, feeding both the ground PV reception system. In this sense, the message of the diagram for a rational on solar power from space implementation is, that it is questionable, whether the pure terrestrial or the space-ground combination should be followed. In the pure terrestrial solution, a growth by continuous extension of solar photovoltaic reception areas is achieved; in the combined case, growth by a continuous enhancement of space radiation is achieved. Basic principle is in either cases that initially the terrestrial photo-voltaic receivers are installed and operated. The same PV-cells would then be used for space laser radiation and solar radiation, whereas the PV-cells provide a considerable enhanced efficiency (e.g. > 40%) for the part of the laser spectrum.

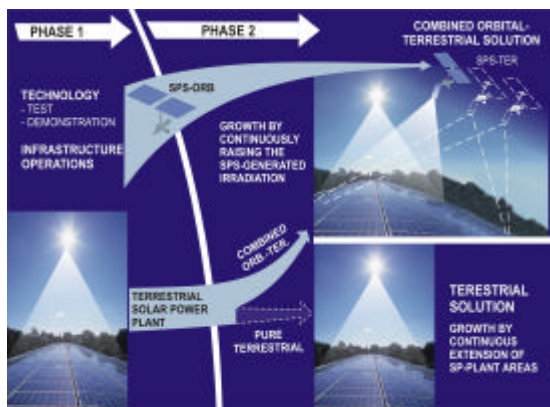


Figure 13: SPS Implementation Options

Thereby reference is made to the ESSPERANS global objectives and energy processing solutions. The European Union Framework Programme 6th ESSPERANS project initiative is aiming to establish the science, technology and social feasibility roadmap, and to develop the knowledge basis and enabling technologies, as well as the European and international socio-political and economic co-operation schemes, for the intensive use of solar energy for electricity and hydrogen generation, combining Very Large Scale Solar Energy Platforms on Earth and Space, as a global, clean, renewable, therefore sustainable, energy production scenario.

Several ways for immediate and CO₂ neutral hydrogen generation technologies are envisaged, such as the technology of photo-catalytic hydrogen generation from water. The solar energy collected on a very large scale could then be used for totally CO₂ neutral electricity production and hydrogen generation through water splitting by using several processes, including electrolysis but also photo catalysis and laser photolysis of water. Direct solar energy pumped laser radiation, for example, could be used for hydrogen generation through laser photolysis of water, which is the most direct route from solar energy to clean, renewable and abundant hydrogen.

A typical example is a solar power reception system coupled with a H₂ production facility (water electrolysis), H₂ storage facilities and fuel cells. During days with appropriate weather conditions (no clouds), electricity production is directly ensured by the receptors (photo voltaic). The production exceeding the market demand is used to produce and store H₂. During night or bad weather conditions, the H₂ stored is used to feed the fuel cells, which will supply the demanded power. Such a solution is well suited to a regional application, meant by the term hydrogen based economy. The station can be connected via a H₂ pipeline to the targeted H₂ grid.

Laser Technology Option for SPS

The reasoning for giving the preference on laser power transmission technology is mainly to avoid the drawbacks of microwave transmission, as they occur of side lobes/spikes and their difficult control in failure cases and the much higher mass and sizing requirements of the transmitting elements compared to the laser system (up to factor of 50), despite the relatively high microwave efficiency and the

technology development status, achieved up today.

The laser technology is preferred versus microwave concerning distinct criteria, but both, microwave and laser technology have been assessed :

- transmission elements size
- side-lobes/spikes issue
- negative impacts of MW (navigation, communication, human / environment)
- laser modular implementation

Summarizing these actual arguments of laser versus microwaves the following could be stated:

- Microwave systems are relatively efficient and have less attenuation by atmospheric effects
- R/F spectral constraints on MW side-lobes and grating-lobes imposed by the ITU result in design and filtering requirements; this leads to reduced efficiency and larger, more costly systems
- Laser systems allow a smooth transition from conventional power to SPS, and offer more useful space applications and open up new architecture solutions
- Electronic laser beam steering probably required to keep mechanical complexity and mass within acceptable limits
- Laser and microwave systems have different design drivers, and due to their potential, laser based systems deserve a comparable consideration
- In terms of launch, transportation and assembly efforts microwave systems are more complex and costly compared to laser systems (big transmitter antenna)

For power beaming from space to Earth there are 3 alternatives for further laser systems development:

Diffusion cooled sealed-off CO2 slab lasers (in combination with thermo-dynamic re-conversion) provide a just acceptable efficiency, which however has little potential to be improved any further. These lasers feature the highest power per unit with still more than sufficient beam quality. Some deficiencies in lifetime need improvement

Nd:YAG lasers combined with photovoltaic re-conversion at reasonable efficiency (silicon cells), however the efficiency of the lasers as of today is not sufficient. Heat rejection is a major problem, slab lasers may be a way out in future

development. High power per unit results in more difficult to handle beam quality

High power diode lasers provide an not acceptable beam quality for this application, because they are, due to the very low power per unit, based on single diodes which are optimised for output power and not for beam quality. Stacking of these devices results in further deterioration of beam parameters, which is not disturbing in near distance focussing, however destroys the beam with respect to long range collimation from GEO

Since beam quality of the single diode has already been improved up to the diffraction limit, there are essentially three potential ways for future development could be,

- Individual collimation optics per diode:

This means that each diode has to have a diffraction limited beam quality ($M^2=1$) with a reasonable power ($> 1W$) and each will be equipped with its dedicated collimation optics. The problem may arise in the alignment and stability of the alignment of the extreme number of tiny emitters needed for power transmission to a defined spot

- Combining the beams of many laser diodes into a single collimation optic

It is assumed that this is only possible by stacking (combined with polarization and wavelength decoupling methods) as used in today power diode lasers and thus will improve the cumulated aperture needed, if the beam quality of the single diode can be kept at high level

- Coherent coupling of diode lasers to form a common wave front.

This implies employing the MOPA concept to multiple amplifiers in parallel. All coupled diodes share the same collimating optics or may even form a synthetic aperture

SPS Technology Spin-Off potential

The synergies from the SPS technology and system developments into the space sector itself and especially in other, non-space areas are conceived as a major driving force, also for pursuing the SPS systems development and implementation itself.

Major spin-off's are under consideration, as

- Power Connection & Switching / Moon & Mars Rover & Stations, Moon & Mars EVA
- Terrestrial Inspection, Reconnaissance Systems, Communication / Remote Sites Energy Supply for Emergencies
- Launcher Stage Power & Data Links / ISS Local Power & Data Links for P/L, Instruments & Modules
- Power Supply for ISS Co-orbiting Science & Technology Platforms
- Power Supply for Orbital Transfer Vehicle/ Platforms /Satellites
- Laser Propulsion for OTV
- Power Supply for Earth Research Applications & Dedicated Remote Users
- High Power Transmission for Orbital Systems in Earth or Planetary Orbits, e.g. Moon
- High Power, Long Distance Transmission for Moon and for Planetary Vehicle (Europa)
- High Power Supply to Earth Users and Energy Grid

Conclusion

The space solar power technology is a enabling for future energy supply systems for beaming energy from space to earth, the so called Solar Power Satellites, for planetary exploration missions involving manned and robotic mission vehicles, and free-flying technology demonstration and material science platforms. The use of laser-photovoltaic wireless power transmission is the key technology for the envisioned future applications. The technology demonstrated and matured in early space demonstrations can also be used in other ESA, NASA and DLR supported missions to planetary bodies and moons. The application for Space Solar Power satellites represents one of the cornerstone scenarios for Earth energy supply in the future together with other means like hydrogen processing. Spin-Off effects for WPT technology use in space and non-space sectors are a driving force for the WPT and SPS implementation in total. The up coming activities should increase the transmission distances, power levels, and efficiencies, the pointing accuracy, and the implementation of data transmission in the power chain, this in preparation for near-term space science and technology demonstration missions. An enhanced test-setup using an airship is envisaged, which could also be seen as a potential application scenario for future planetary exploration missions.

Abbreviations

EPFL	Ecole Polytechnique Federale de Lausanne
GaInP	Gallium Indium Phosphite
I/O	Input/Output
ISS	International Space Station
Nd:YAG	Neodymium doped Yttrium-Aluminium Garnet
PV	Photovoltaic
SPI	Solar Power Infrastructure
SPS	Solar Power System
WPT	Wireless Power Transmission

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