Solar Power Satellite

SPS-REPOSE STUDY

September 2004

ESA Contract N° 17761/03/NL/MV

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Executive Summary

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Author : C. Cougnet

Study team:

C.Cougnet, E. Sein, D. Loche (EADS Astrium)

A. Celeste (University of La Reunion)

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1 INTRODUCTION

Power generation is one of the crucial elements of space vehicles and of future infrastructures on planets and moons. The increased demand for power faces many constraints, in particular the sizing of the power generation system also driven by eclipse periods and the solar intensity at the operational spot.

In the medium term, Earth orbiting platforms will require higher power levels. Interplanetary exploration vehicles face the problem of distance to the Sun, especially when large amount of power may be needed. Large infrastructures on Moon and planets, like Mars, are constrained by environment attenuation, long eclipse or distance to the Sun.

New systems and technologies have to be found, which go beyond simple improvements of the current technologies.

Solar Power Satellite (SPS) systems, based on wireless power transmission, are attractive candidate solutions to provide power to space vehicles or to elements on planet surface.

Studies have been carried out for many years on the problem of providing renewable electrical energy from space to Earth with SPS.

This study aimed at assessing the utilisation of Space Power Satellite to provide power to satellites, platforms, interplanetary vehicles or elements /infrastructures on Mars or Moon surfaces.

To achieve this objective, the study has:

- analysed the technical feasibility of the SPS power delivery system: key parameters, RF and laser power transmission systems (technologies, limitations and constraints), power generation
- assessed the candidate SPS system architectures for the selected missions and its viability for space applications.

This study has been performed by EADS Astrium SAS, with the Université of la Réunion.

Technicatome gave a support for the thermo-electrical energy conversion aspects.

2 SYSTEM ASPECTS

SPS system

The SPS system is illustrated on Figure 2/1. It is composed of:

- The power generation system (solar cells, concentrators or other).
- The power transmission system, including the conversion of electrical energy and the generation of the beam. Both laser and RF transmission systems have been considered.
- The power receiver system, which is closely linked to the laser or RF technology

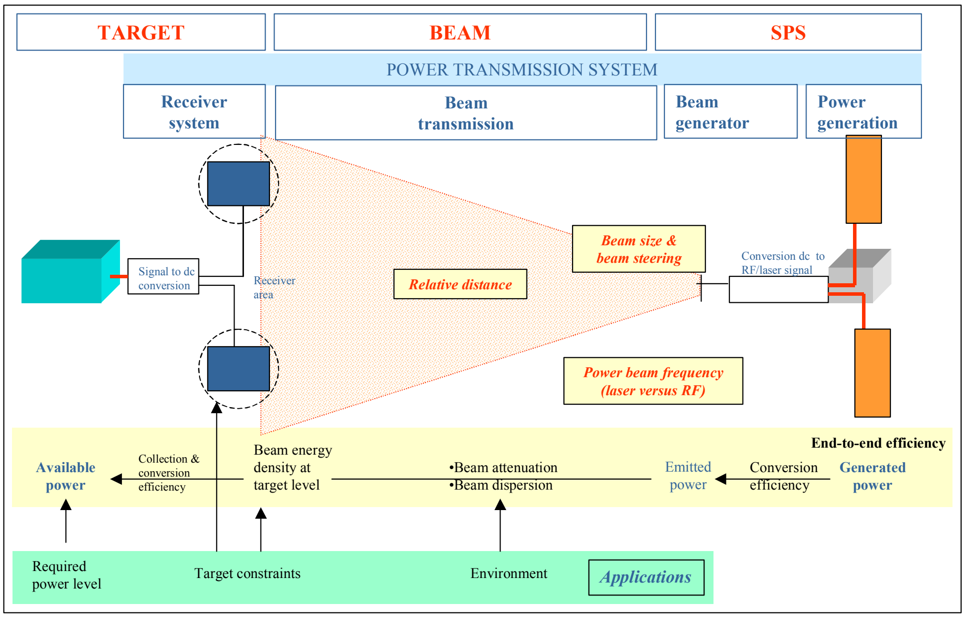


Figure 2/1: SPS system overview

SPS system parameters

The definition of the SPS system (Figure 2/2) depends on the user needs and constraints (e.g. target location, required power, receiver size, environment, target mobility), which vary according to the application. Based on these constraints, two main system drivers influence drastically the system definition and size: the power transmission system type (RF or laser) and frequency (or wavelength) and the SPS position, which defines the SPS-to-target distance and the sun visibility.

Then, the definition of the system parameters (e.g. emitted power and emitting surface size, power density at target level and receiver surface) will drive the allocation of performances between the SPS and the receiver system and subsequently their respective sizes. As they are linked, an adequate compromise has to be found between these parameters to optimise the complete system. In some applications, the receiving surface size is a user constraint. Beam steering is also a system parameter depending on the user mobility, and on the SPS location.

The technology is a key element in the definition and performances of the SPS and of the receiver system. It also influences the selection of the system parameters. In this study, current and reasonably achievable technology state-of-the-art has been taken into account to carry out a preliminary evaluation of both SPS and receiver system and get a starting basis. Nevertheless, at the time of utilisation of the SPS, advanced or new technology with significantly improved performances could be expected.

The optimisation of the SPS system can be done according to different possible criteria: optimisation of the overall system performances (in terms of overall efficiency, SPS and receiver mass, implementation scenario, etc), optimisation of the SPS design (mass, efficiency, technologies, power), or optimisation of the receiver system (efficiency, surface, mass). The preferred criteria will depend on the applications.

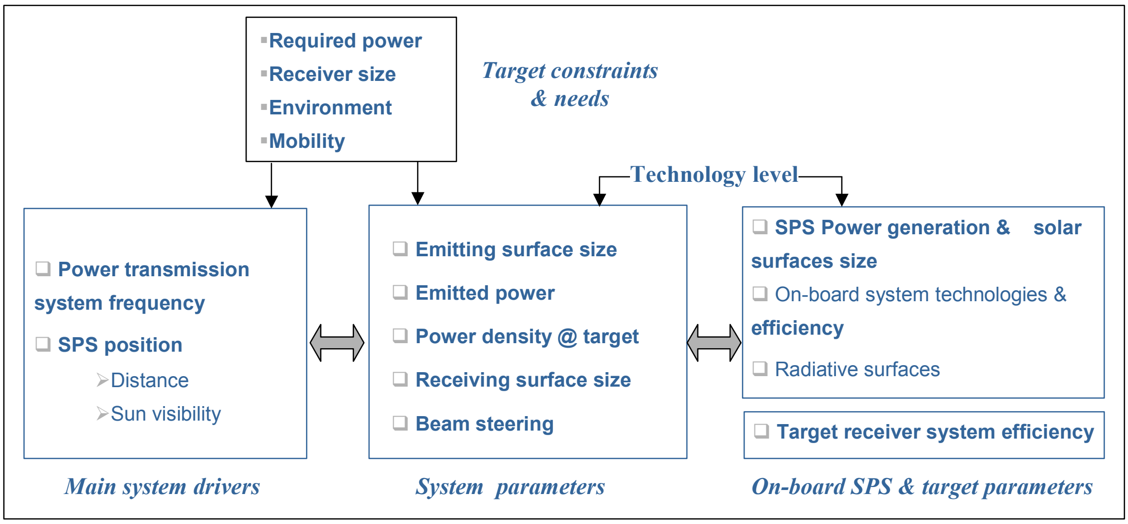


Figure 2/2: System key parameters

Differences with space-to-Earth applications

The constraints generated by the space-to-space applications are significantly different from the ones coming from the space-to-Earth applications. Thus, in the case of space-to-space applications:

- The user needed power is much lower (0,5 to 100 kW instead of MW to GW)
- The range of SPS-to-target distances is much larger
- The receiver surface may be restricted by the user
- The target may be fixed or mobile
- The environment is different

In the case of power delivery to a Mars base, which appears the closest to the space-to-Earth application, the SPS-to-target distance is in the same order of magnitude, both targets are fixed, and there is no constraint on the receiver surface, although it should be limited on Mars due to the implementation scenario; but the required power is much lower, the atmosphere attenuation is different (with occurrence of dust storms on Mars), and the solar flux density at the SPS around Mars is much lower.

3 POWER TRANSMISSION SYSTEM

3.1 RF POWER TRANSMISSION SYSTEM

The power density created by the projecting aperture at the centre of the collecting antenna, situated at a distance r, is:

$$dP = 0.709 \cdot \frac{P_{proj} D_p^2}{\lambda^2 r^2} \qquad (1)$$

This assumes that the projecting antenna is a circular aperture of diameter D_p with a circularly symmetric illumination and linear polarization, the illumination distribution in the antenna aperture is a 10dB Gaussian taper, the collecting antenna is circular with diameter D_c and the projecting and collecting antenna axes coincide.

If the power density is assumed to stay essentially constant over the entire collecting antenna aperture, which is the case in almost all the reviewed applications, the following collected power to projected power ratio expression can be derived (referred to as the aperture coupling efficiency):

$$\frac{P_{collected}}{P_{projected}} = 0.556 \cdot \left(\frac{D_p D_c}{\lambda r}\right)^2 \qquad (2)$$

The Figure 3.1/1 illustrates the sensitivity of this aperture coupling efficiency to the projecting antenna diameter when the SPS is in Mars areosynchronous orbit (17000 km).

The performance of the RF power transmission system has also to take into account the efficiency of the SPS RF generator and transmission equipment, of the RF beam and of the collecting antenna, rectifying circuit and regulator. This is summarized in Figure 3.1/2.

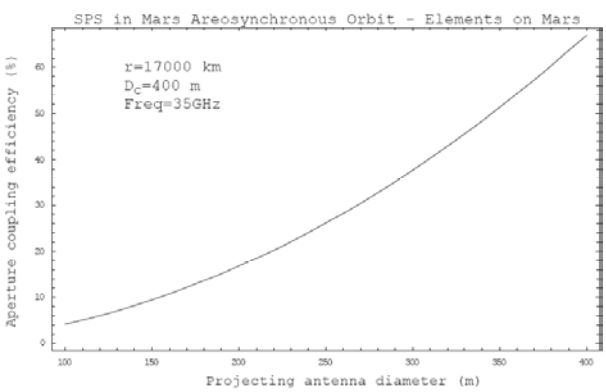


Figure 3.1/1: Illustration of aperture coupling efficiency

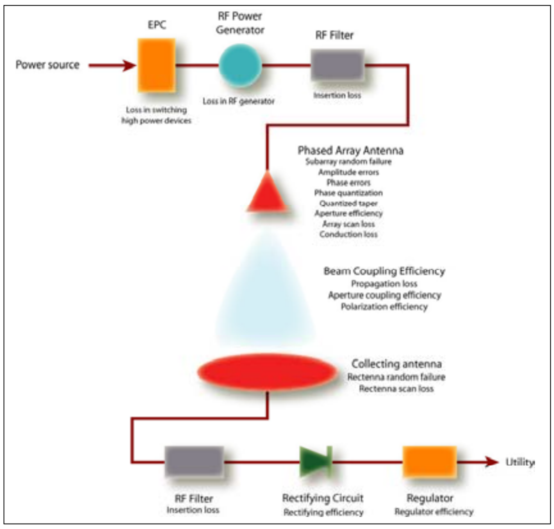


Figure 3.1/2: RF power Transmission System

The dimensioning of the RF power transmission system results from an adequate balance between the definition and sizing of the receiver system (rectenna) and the definition of the SPS transmitting system (projecting antenna and signal generator), the transmission frequency being the key driver of these definitions. The definition of rectenna elements, starting point of the dimensioning process, includes items like the optimum input power at the rectifying circuit for maximum conversion efficiency, gain or effective area of the associated antenna and efficiency of the antenna. With these definitions, it is possible to estimate the optimum power density at the rectenna and the collecting area aperture diameter necessary to provide the required DC output power. Equation (1) is then used to derive the projecting system diameter and total projected power. Finally, generator and antenna technologies are identified for emitting the required RF power from a DC power source. Performance estimation is then possible as a final stage of selection between identified technologies.

This first approach is subsequently modified in cases where beam steering is necessary, to account for beam steering angle and allowed grating lobe levels although these parameters are not as crucial as they are in SPS designs for power delivery to Earth.

Frequency is a very important parameter; indeed, the aperture coupling efficiency for given antenna size increases with the square of the frequency. Most of the RF power transmission systems in SPS designs have used 2.45GHz and 5.8GHz ISM band frequencies, mainly because of the low attenuation by the Earth atmosphere of these frequencies.

For space-to-space applications, beam attenuation by atmosphere is only a concern in the case of power beaming to the surface of Mars. However, recent work at NASA demonstrated that the Martian atmosphere is usually much more transparent to RF than the Earth atmosphere and gave estimations for different frequencies. On the other side, at higher frequencies components are generally not performing as well as they do at low frequencies, and cost and thermal dissipation issues are also increasing sharply when entering the millimetre wave region. Consequently, there is a choice in frequency with an optimum balance.

A review of the most promising technologies at frequencies ranging from 1GHz to more than 100GHz has shown that a frequency of up to 35GHz is acceptable with regard to the available technology performance and cost. Mars atmosphere attenuation is still reasonable (estimated to be 3.5dB at azimuth). Rectennas have also been demonstrated with efficiencies of 74% and it is conceivable that better results could be achieved in the future.

Even at 35GHz, for the considered distances, high aperture efficiencies can only be achieved with a large emitting antenna or a large collecting antenna. In the case of Mars for instance, using a small emitting antenna on an SPS in areosynchronous orbit, would produce at the surface power densities lower than the power density from the Sun. Nevertheless, we have analysed the interest of such a system using a small diameter antenna when it comes to continuously provide power during large dust storms, based on the advantage that microwaves are not influenced by the presence of dust.

3.2 LASER POWER TRANSMISSION SYSTEM

The laser power transmission system is mainly driven by the receiver technology (photovoltaic for the visible and near infrared, thermal conversion system for the infrared), and the distance between emitter and receiver.

The single space based laser is the straightforward approach: one satellite points the receiver area with a diffracted limited beam. A constellation of space laser satellites can be imagined, adding their respective power. This configuration requires a pointing accuracy in the range of tens of nano radians, which is challenging with large optics. The diameter of the emitting optics could be as large as possible to reduce the required emitting power, but is limited by the integration constraints. Future technology for large telescopes are expected to achieve 10 to 20 m diameter mirrors.

A space based laser array configuration allows to virtually increase the telescope diameter. High power lasers (slaves) are fed by a stable and frequency controlled low power laser (master), forcing the slave to emit on the same frequency. The intersatellite distance has to be controlled very accurately. One of the main features of the constellation control is the open loop target acquisition using guide stars.

Several laser technologies have been reviewed in the visible and infrared ranges.

In the visible range, the solid state lasers are considered as the best candidates for the solar power application. They can rely on a laser diode or on solid state material like Nd-Yag. The laser diode is the most efficient laser, with an up to 80% plug-in efficiency and an emitted wavelength in the range of 795-850 nm. The most important development effort is made for diodes emitting in the range of 950 nm (pumping of 1.55 µm fiber laser). Large area emitting system with thousand individual diodes could be realised, the main limitation being the thermal control of such diode panels to maintain optical coherence. These are however interesting candidate, at least for optically pumping solid state laser.

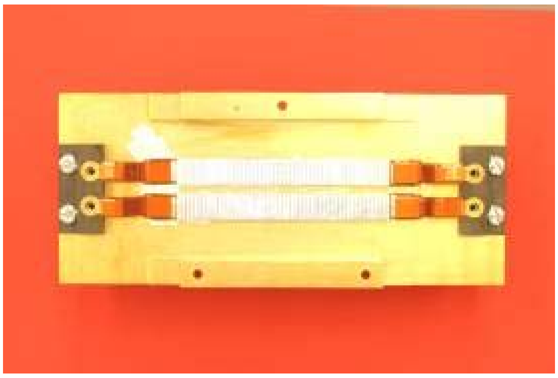


Figure 3.2/1: Laser diode (from Laser Diode Inc Web page)

Most of the solid state lasers are based on crystal technology (Nd:Yag, $Nd:Y_2O_3$, Ruby, etc). These lasers are optically pumped in the visible range. The Nd:Yag laser (1.064 µm) is the most widely used; it can be efficiently pumped by laser diodes or solar radiation. Visible radiation at 0.532 µm can be emitted. The overall efficiency for the laser diode pumped system is about 15%. For a solar pumped system, a careful detailed calculation has to be made in order to evaluate the real system efficiency (ratio between solar collector surface and solar panel surface). A fiber laser with optimised sun collector could be an interesting alternative, with efficient optical power conversion, but no experimental results are yet available.

Thus, for the studied applications, a solid state diode pumped laser has been preferred, as it is an existing technology, while the sun pumped laser technology is not mature today.

A disk laser configuration has been selected due to its low sensitivity to thermo-optics distortion. The emitted power is achieved by using several disk laser modules, as illustrated on Figure 3.2/2.

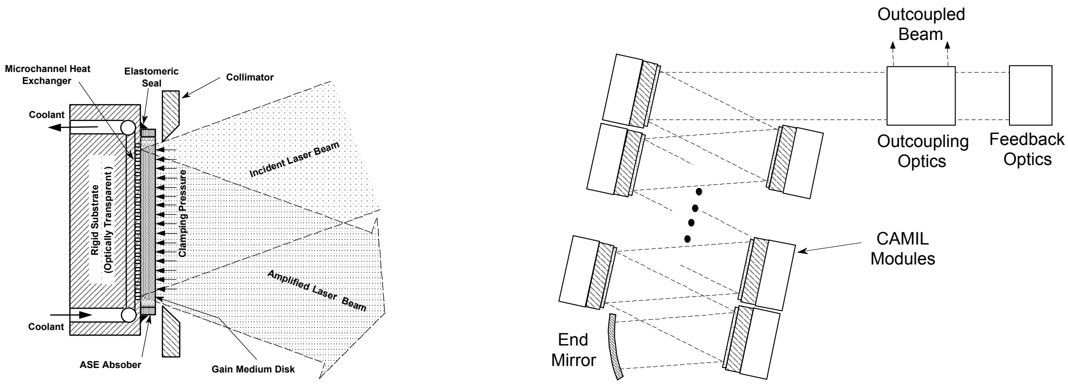
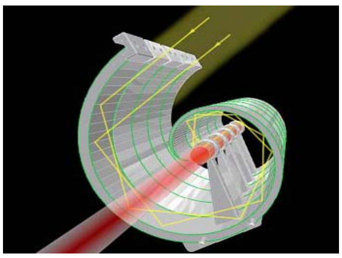


Figure 3.2/2: Laser system configuration (from ([11])

In the future, direct solar pumping seems an attractive approach. The recent development of hollow fiber lasers offers new flexible solutions for a potential efficient solar power conversion.



Solar pumped fiber laser

Fiber Bundle

Figure 3.2/3: Future trends (from [13])

In the IR domain, the CO_2 laser remains the most interesting candidate. The emitted wavelength is 10.2 µm. A plug-in efficiency of 10% could be obtained with a correct dissipation of the thermal energy. CO laser technology could also be envisaged.

4 REVIEW OF APPLICATIONS

The SPS system is applicable to several types of missions. It could provide power to Earth geostationary platforms (representative of Earth orbiting missions), to a transfer vehicle to Mars (representative of interplanetary missions), to a rover or manned base on the Martian surface, or to an element on the Moon. These missions are representative of a wide range of applications, each having its particular constraints and needs.

4.1 POWER DELIVERY TO GEOSTATIONARY PLATFORM

The delivery of power to GEO platform should be done with minimum impact on the platform design. Consequently, a laser based SPS is proposed, the platform solar arrays being used as receiver surfaces. The SPS would provide power during the eclipse period of the platform. It should preferably be located on a sun-synchronous orbit 6-18h, which allows fixed SPS solar surfaces facing permanently the sun, and 100% availability of power during platform eclipse.

The interest of this SPS application would be to provide a service to all GEO platforms during eclipse. To that aim, the SPS system should provide a redundancy capability, and power to several satellites simultaneously. However, the potential gain for the platforms (some batteries and associated equipment) does not appear cost effective.

4.2 APPLICATION TO DARWIN MISSION

The utilisation of the SPS concept for the Darwin mission (Figure 4.2/1) is an alternative solution to the present configuration. It allows to isolate the Darwin constellation from the solar flux by means of a large multi-layer solar sail. This solar sail has its own structure and attitude control subsystem; it would have a diameter of 550m and be located at 200m from the constellation.

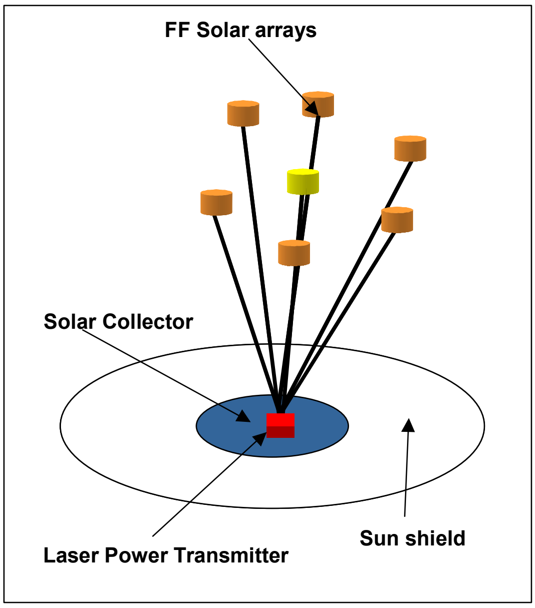


Figure 4.2/1: Darwin alternative concept

It includes a laser power transmission system that provides power (1.5 kW requested) to each of the free flyers. The individual power flux has to be tuned to minimize the optical pressure differential torque. Due to the relative short distance between the transmitter and the receiver, a classical fibered laser diode is selected. It is an existing equipment, working at 0,808 µm wavelength, which can be space qualified. This laser shall have a numerical aperture of 0.2, an emitted power of 4 kW CW and a multimode fiber coupled with 1mm fiber core. The pointing accuracy (1.1mrad) is easily achievable. A power of 2.24 kW would be available at the user level. For the complete constellation, about 300m² of solar cells have to be installed on the solar sail. The size of the free flyer solar panel is 1 m². The laser transmission system technology is already existing and space qualified.

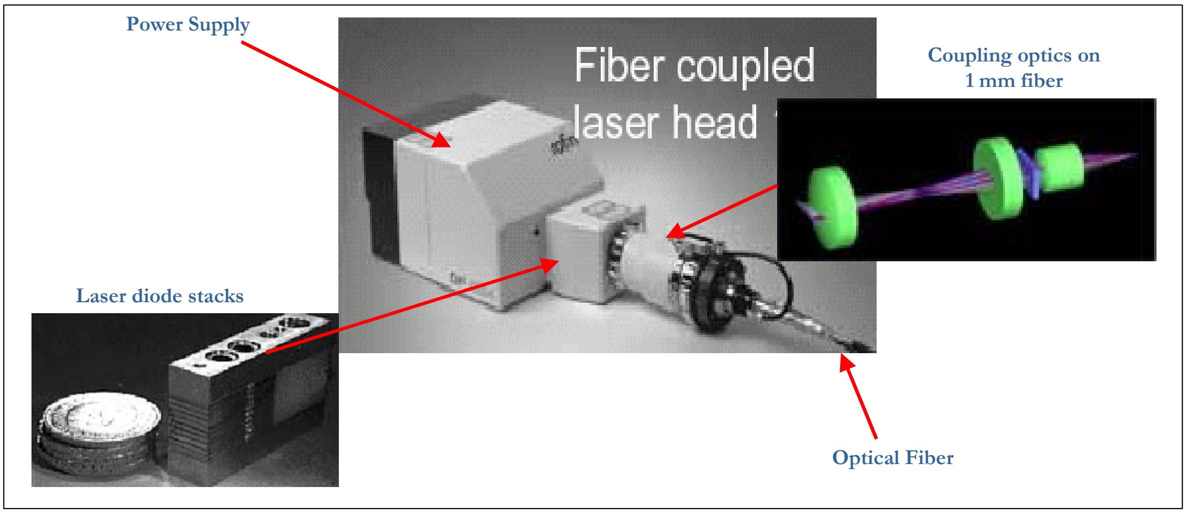


Figure 4.2/2: Laser diode system for Darwin application (from ([8])

4.3 POWER DELIVERY TO INTERPLANETARY VEHICLE

The delivery of power to Mars transfer vehicles is characterized by the distance of transmission, which remains at about 65 Mkm with adequate positioning (in Mars orbit) and utilisation of SPS.

For such distances, a laser transmission system is used. The proposed SPS system consists of a laser satellites array, composed of one common master laser and TBD slave laser satellites equally distributed to represent a large array diameter. For instance, a system of 30 slave laser satellites emitting 10 kW each and representing an array of 150 m diameter provides 1.2kW at user level, assuming a receiver surface of 1000 m². The resulting power density at receiver level is around 2.5 W/m2 that is lower than the power density delivered by the Sun at that distance.

The positioning proposed for a vehicle to Mars is not necessarily applicable to a vehicle travelling towards further planets. Positioning the SPS further than Mars raises the problem of solar energy density at long distances. To provide energy to interplanetary vehicles does not appear an attractive application for SPS.

4.4 POWER DELIVERY TO ROVER ON MARS

The objective is to permanently provide power to a small rover on the Mars surface. The rover requires 500 W in operating mode and 50W in dormant mode. Its receiver surface is a square panel limited to a maximum size of 3m. The key environmental constraints are the potential dust storms, during which the rover would remain in dormant mode.

SPS positioning and power transmission system

The SPS is preferably located on an areosynchronous orbit (17000 km altitude in the Mars equatorial plane). It will remain permanently in visibility of the rover, with some short eclipses around equinoxes.

At that distance, an RF power transmission is strongly penalised by the small size of the target. Besides, positioning the SPS in low Mars orbit would result in a very low availability (a few % of time). For this application, the SPS is therefore based on laser power transmission with photovoltaic cells on the rover.

A key issue for the laser transmission is the occurrence of dust storms. It is assumed that the behaviour of the laser beam allows the rover receiver surface to collect enough energy for its dormant mode (that means at least 10% of the nominal case), except in period of peak of optical depth, assumed to last less than 5 days (sizing case for rover batteries). The rover is also assumed to be equipped with adequate countermeasures to sweep the dust off the solar cells.

Laser power transmission system

The proposed power transmission system is composed of 4 independent laser systems, with a 1.5m telescope and capable of 6 kW emitting power. It is based on existing solid state diode pumped technology, with a disk laser configuration.

The major critical item is the extremely accurate pointing system (86,2 nrad pointing accuracy) that has to be developed to direct the focused beam towards the rover. A rover position acquisition process has to be defined. It would rely on a small laser beacon or corner cube (typically 5 cm diameter) implemented on the rover, and a receiver optics (typically 10 cm) on the SPS. Each telescope is actively controlled to achieve the fine pointing requirement. The rover receiver surface is equipped with optimised solar photovoltaic cells for 1.06 µm, with a 50% efficiency (to be developed). The spot dimension at rover level is about 14.4m diameter, larger than the receiver area. 650 W are available at user level.

SPS system concept

The SPS system is illustrated in Figure 4.4/1. The power generation is ensured by two solar arrays using multiple junction solar cells with small concentrators. There is an independent power distribution system per laser, each based on a 100 V regulated bus. Deployable radiators have been implemented at both solar arrays and laser system levels. The overall system efficiency is about 0,6%, and the SPS mass at launch about 40t for a diameter of 5m. It is transferred from LEO to Mars orbit with its electric propulsion system.

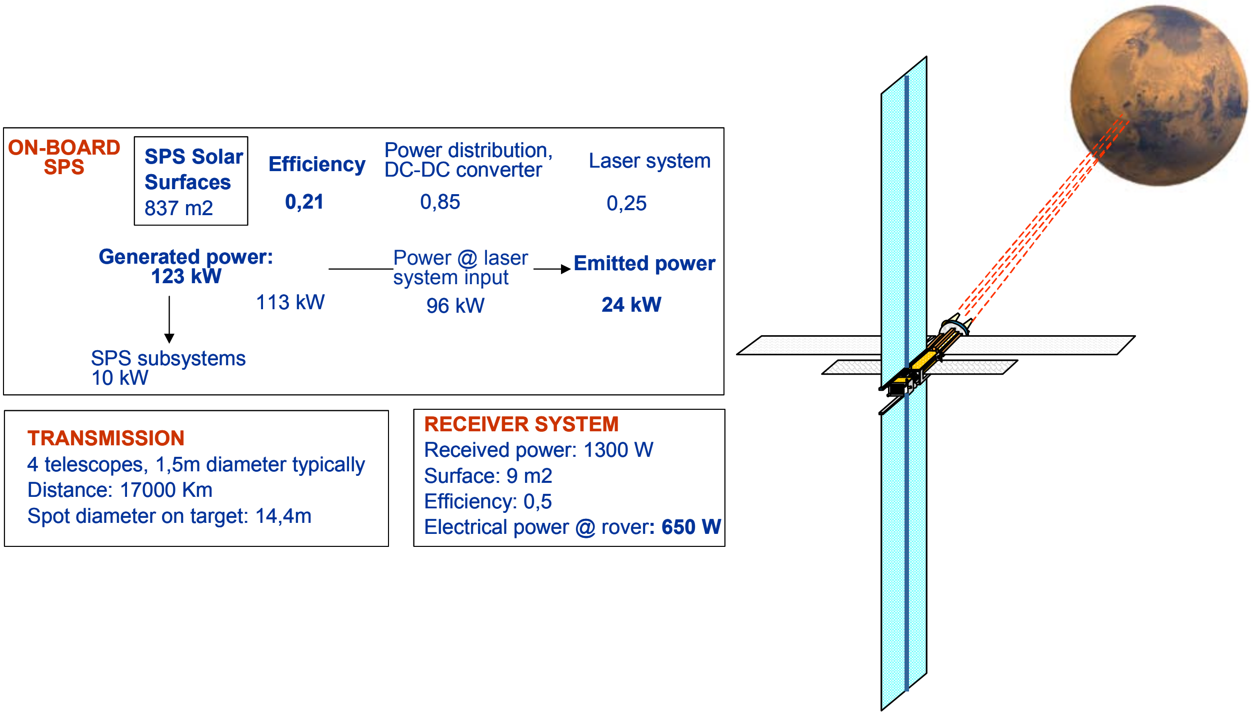


Figure 4.4/1: SPS system concept and performances for Mars rover application

These 40 tons in LEO for delivering only a few hundred watts to the Martian rover might seem orders of magnitude too much compared to alternatives at first sight, but one needs to consider that:

- these estimations are based on current or reasonably achievable technologies,

- this system allows the rover to be operational all the time (day and night), except in case of dust storm

- such a system would have a lifetime of 20+ years and could flexibly serve many missions (covering almost half of the planet!)

- such a system would also be able to deliver about 10 kWe to a larger base, with a larger receiver surface

- a 40 tons system mass in LEO would allow to implement on the Martian surface a power system of about 3 to 5 tons (depending mainly on propulsion system and entry technology)

4.5 POWER DELIVERY TO MARS BASE

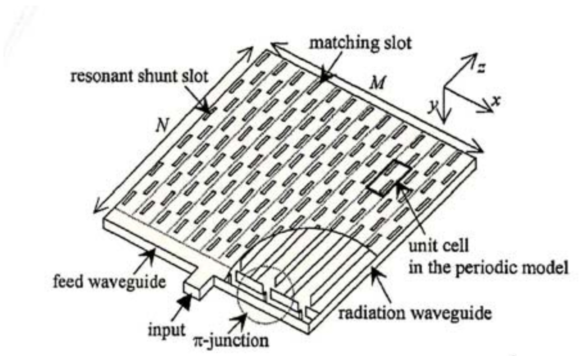
The Mars base would be composed of several elements and implemented on an area of about 1 km diameter. It is assumed to require about 100 kW permanently. The SPS receiver surface could be located at a safe distance of the Mars base.

The SPS is also located in areo-synchronous orbit. Although penalised by the distance, the RF power transmission is preferred, because size constraints on the receiver can be somewhat relaxed for this application while laser transmission is still sensitive to dust storms.

RF power transmission system

The receiver system will be composed of Rectennas. Several types of rectenna have been defined, all based on current technology state-of-the-art. A low power density rectenna has been selected to minimize the on-board projecting antenna sizing. Each rectenna is a metallised foam flat waveguide slot array. The Figure 4.5/1 illustrates a rectenna element and its sizing features. An automated fabrication on Mars might be possible using special forming and metallization equipment.

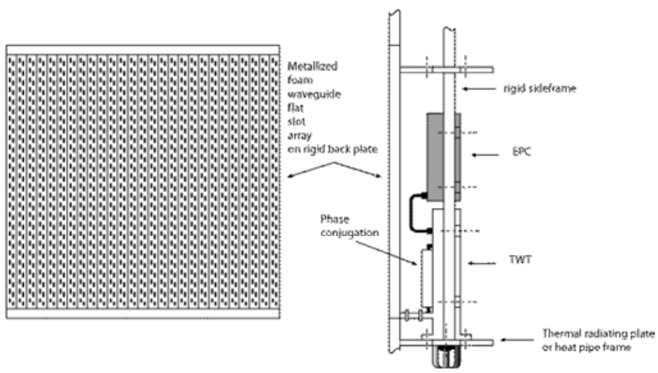
The proposed transmitting system includes 100 W TWT/EPC modules and a 132m diameter slot array antenna. A retrodirective phase conjugation circuit ensures the adequate beam pointing of the arrays towards the rectenna. The emitting power is 2 MW. The average power density at transmitting area is 146W/m² with a maximum of 374W/m² in the centre. Figure 4.5/2 illustrates the slot array technology.



(source ref[6])

Power density @ rectenna	1,51 W/m^2
RF power @ rectifying circuit	21mW
RF to DC conversion efficiency	65%
DC output power density	0,42 W/m^2

Figure 4.5/1: Rectenna technology and features



26680 modules EPC/TWT

module size: 0.7m x 0.7m x 0.03m

Figure 4.5/2: On board slot array antenna technology

SPS system concept

The power generation is ensured by solar cell surfaces (more than 42 000 m²) mounted on North-South trusses with a clearance (typically 60 to 100m) from the SPS axis to avoid any occultation by the appendages. There are independent power distribution systems per panel, each based on a high voltage (1000 V) regulated bus.

Two SPS concepts have been defined (Figure 4.5/4), depending on the type of antenna. The SPS concept with parabolic antenna is composed of eight modules around a central core. Each module includes an antenna reflector (50m diameter), one set of sources, TWT with its EPC and electronics, a deployable radiator (around 1000 m²) and an active thermal loop. The SPS concept with the slot array antenna includes a large flat antenna (132m) mounted on a central core. Each slot array element is integrated with its TWT, EPC, electronics and its radiator surfaces protected with baffles. In each concept, the central core houses a primary reflector, electronics, communications, and electrical propulsion, and supports the two solar arrays trusses. The SPS system performance is summarized in Figure 4.5/3. The overall system efficiency is about 1,6% and the SPS mass is in order of 500 tons. The SPS is assembled in Low Earth Orbit, and then transferred to Mars orbit with its electric propulsion system.

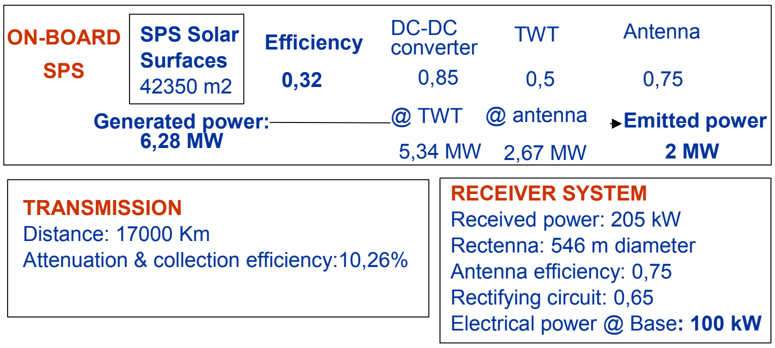


Figure 4.5/3: SPS system performances for Mars base

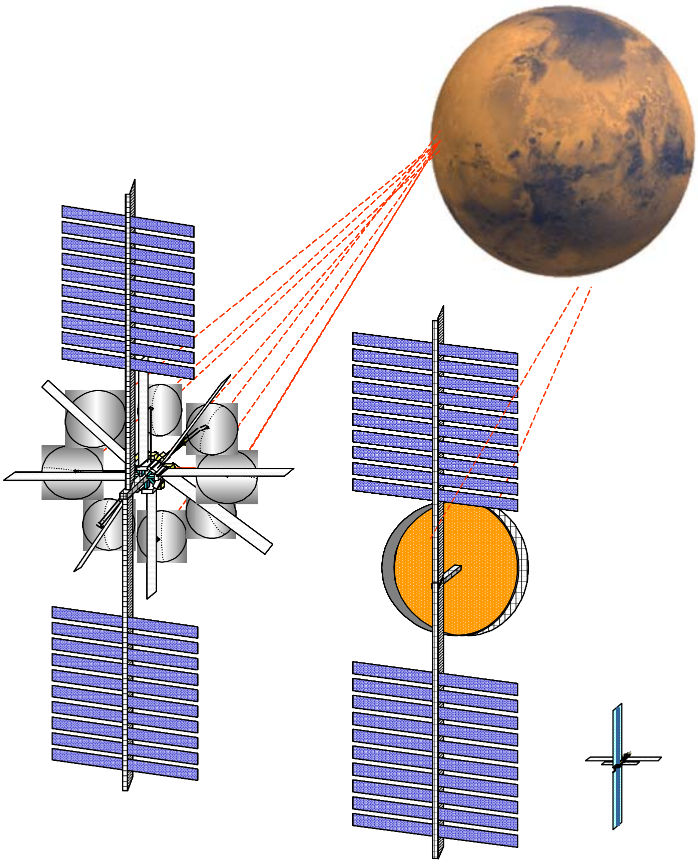


Figure 4.5/4: SPS system concept for the Mars base application

4.6 POWER DELIVERY TO MOON INFRASTRUCTURE

The Moon infrastructure is assumed to need permanently a few tens of kW. The SPS has to provide power at least during the eclipse, which lasts up to 14 days. There is no constraint on the receiver surface. Both laser and RF systems are applicable.

RF based SPS system

The RF based SPS would be located at low altitude and low inclination (typically 5000 km, 10°). Power delivery is limited in target latitude. The SPS availability is 33% maximum of its orbit, so that 3 SPS are necessary to provide power permanently.

The RF transmission system, at 35 GHz, is composed of a large antenna (88m diameter) of HCPA type. The signal generator is ensured with about 10 000 RF modules, each including an antenna module, EPC/TWT and phasing circuit. 5000m² of solar surfaces are installed generating up to 2 MW and the radiator surfaces are mounted on the back of the antenna structure. The receiver system on the Moon surface is a rectenna of roughly 400m diameter. The system provides 50 kW to the infrastructure. The SPS mass is in order of 180t. The overall system efficiency is about 2.5%. The system performances are recalled on Figure 4.6/1. An illustration of the SPS is given on Figure 4.6/3.

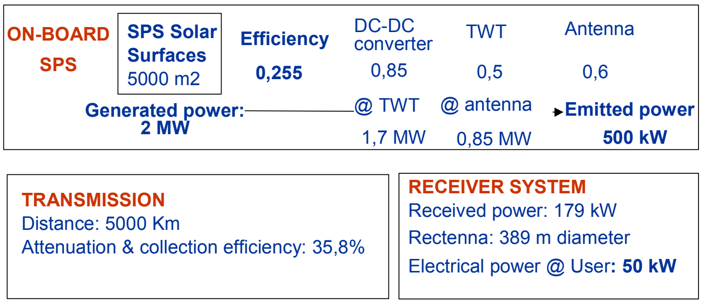


Figure 4.6/1: RF based SPS system performances for Moon

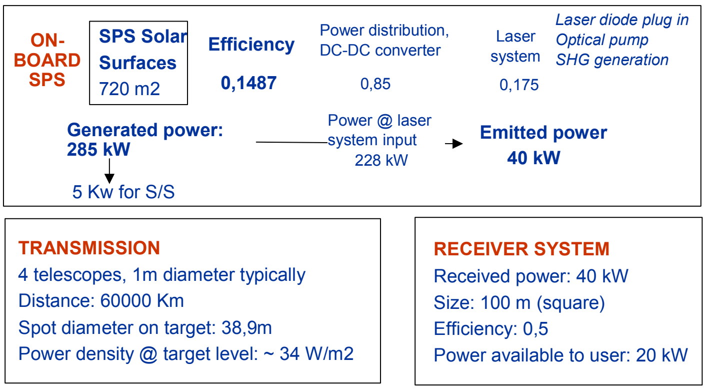


Figure 4.6/2: Laser based SPS system performances for Moon

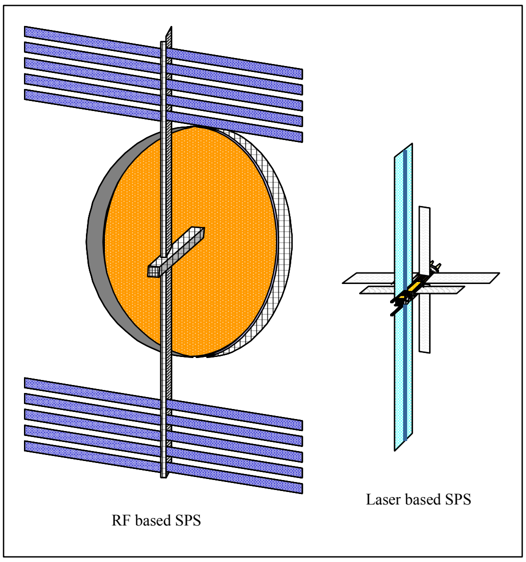


Figure 4.6/3: SPS system concepts for Moon

Laser based SPS system

The laser based SPS would be located in Earth-Moon Lagrange point L1 or L2, as function of infrastructure implementation, at a distance of about 58 000 Km from the target. It could provide a permanent illumination of any spot of roughly half the Moon.

The laser transmission system is composed of 4 Nd-Yag lasers, each capable of 10 kW and having a 1m diameter telescope. The SPS includes one power system and one deployable radiator (about 120 m^2) per laser module. 720 m^2 of solar surfaces are installed generating up to 285 kW. The receiver system is a 100m square surface of photovoltaic cells. The system provides 20 kW to the infrastructure. The SPS mass is about 25t and the overall system efficiency around 7,1%. Figure 4.6/2 recalls the SPS system performances.

5 SPS SYSTEM ASSESSMENT

A preliminary evaluation of the SPS system concepts for various applications has been done. It has been based on current or reasonable achievable technology State-of-the-Art. It has allowed to assess the utilisation of the SPS system for different applications, concluding in its interest for providing power to elements on planets or Moon. In addition, this preliminary evaluation has led to identify the key issues of the concepts, the major drivers of the mass budget and the areas of improvement.

Key issues and sizing drivers

Key issues are linked to the technologies, but also to the required performances. Among others, there are:

- The pointing accuracy of the laser beam, depending on the application. Thus, the Mars rover application requires a target acquisition process and an active control of the telescopes.
- The behaviour of the laser beam through dust storms
- The locking of the RF beam on the target, which relies on a retrodirective phase conjugation
- The slot array antenna size, assembly and thermal stability
- The sharing of performances between on-board and ground (target) for the RF system
- The heat dissipation
- The sizing of electric propulsion, in particular in terms of gas (Xenon)
- The sizing of the SPS, especially for some applications, with impacts on the launch scenario.

In addition, this preliminary evaluation has raised some drivers of the SPS system sizing, such as:

- The low on-board efficiency and end-to-end system efficiency (a few percent)
- The large deployed surfaces (solar arrays and radiators)

- The truss and the cabling
- The RF equipment and rectenna utilisation at 35 GHz

Axes of improvement

Considering the term of the applications, the proposed SPS system performances can obviously be significantly improved. To that aim, several approaches could be followed:

- The improvement of the overall system end-to-end efficiency would have a drastic impact on the SPS mass and size
- The utilisation of new technologies for the power transmission system; for instance, solar pumped laser or new types of fiber laser, or RF generator or rectenna technologies adapted to 35 GHz should bring better performances
- The utilisation of advanced or new technologies in the mass driver areas (power generation cabling, heat dissipation, structure) could result in higher energy density, lighter material, etc.
- The optimisation of the complete system, SPS and receiver. It should ensure an adequate balance between the mass in orbit (SPS) and the mass on the surface, taking into account the constraints of installation on the planet (descent and landing, integration and/or manufacturing on site).
- The analysis of SPS concepts alternative to the large platforms: the utilisation of a network of satellites, offering a larger virtual emitting diameter, could be interesting as solving a number of technical issues.

6 CONCLUSIONS

The SPS system appears as a promising solution for power delivery to elements on planet surfaces. In both Mars and Moon cases, it could be a solution for users, which face the problem of either low solar energy density and environment attenuation or long eclipse duration. It appears as the today only alternative to nuclear energy. The SPS concept could also be an alternative solution to technological issues like in the case of the Darwin mission.

Two power transmission systems were considered based on laser and RF. Laser systems are well adapted to long distance and/or small receiver surfaces, but are penalised by the potential attenuation in the Mars atmosphere, in particular because of dust storm. Analyses would be necessary to assess the laser beam behaviour in that case. The RF system appears advantageous at short distances, and is better adapted in the Mars case when no constraint is applied on the receiver surface.

A preliminary evaluation of the SPS systems concepts has been done, based on current or reasonably achievable technology, as a starting point. This leads to an overall system efficiencies of a few percent, and to important SPS masses, but shows that the laser based SPS is compatible with a single launch (with a possibly heavy launcher) in LEO.

A high potential of improvement exists for the SPS system from the concept presented in this preliminary evaluation, through utilisation of new technologies, optimisation or new concepts, which makes it an attractive solution for these kinds of applications.

To consolidate the interest of the SPS system for elements on planets or Moon, an analysis of the sensitivity of the concepts to the driving parameters would allow to estimate the achievable performance and the objectives for the technology survey; in parallel, the satellite network concept to provide power to Mars base should be assessed, so that the most promising SPS configurations and missions could be raised and analysed, taking into account the scenario of implementation and operations, the failure cases and the impacts on user.

7 ABBREVIATIONS

DC	Direct Current
EPC	Electrical Power Conditioning
GEO	Geostationary Earth Orbit
GW	GigaWatts
HCPA	Hybrid Coupled Planar Antenna
ISM	Industrial, Scientific and Medical (RF spectrum allocation)
LEO	Low Earth Orbit
MW	MegaWatts
RF	Radio Frequency
SPS	Solar Power Satellite
TBD	To Be Defined
TWT	Travelling Wave Tube

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