SOLAR POWER SATELLITES FOR SPACE EXPLORATION AND APPLICATIONS

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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 paper reviews the main results of an ESA funded study, led by EADS Astrium with the support of the Université of La Réunion, which assessed the utilisation of SPS concepts for space-to-space and space-to-planet applications.

2. SYSTEM ASPECTS

The SPS system (Fig 1) 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.

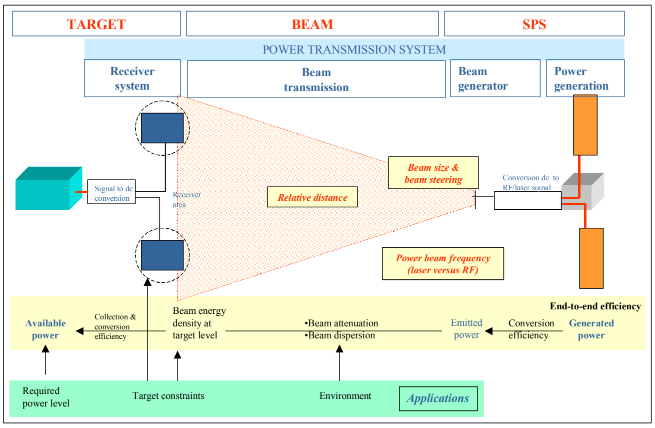


Figure 1: SPS system overview

Figure 2 summarizes the main SPS drivers and parameters, and their interrelation.

The main system drivers are the user constraints and needs (required power, receiver size, environment, mobility), the frequency (or wavelength) of the power transmission system and the SPS position, driving the SPS-to-target distance and the sun visibility.

The main system parameters will size both the SPS and the receiver parts of the system. They concern the transmitting surface, the emitted power, the power density at target level and the receiver surface. All these parameters are linked and an adequate compromise has to be found to optimise the complete system. In some applications, the receiving surface size is a user constraint.

Based on these system parameters, both the SPS and the receiver system characteristics may be derived, in particular the SPS solar arrays size, the on-board system technologies and efficiency, the heat dissipation surface, or the target receiver system efficiency.

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.

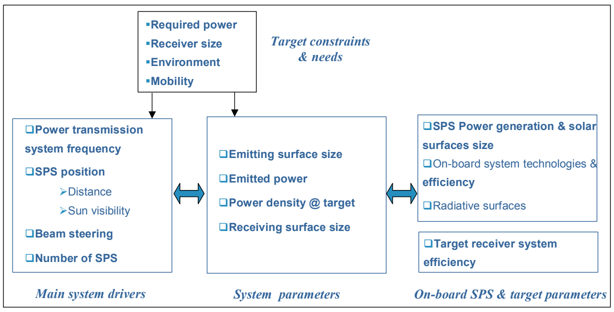


Figure 2: System key parameters

3. WIRELESS POWER TRANSMISSION TECHNOLOGIES

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:

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

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):

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

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 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, it appears from equation (2) that high aperture efficiencies can only be achieved with a large projecting antenna or a large collecting antenna, for distances like the ones foreseen for the studied applications. In the case of Mars, using a small projecting antenna produces at the surface of Mars power densities not considerably higher than the power density from the Sun. Consequently, large projecting antenna diameters are preferable. Nevertheless, a system using a small diameter antenna has been studied in detail because it may be used to continuously provide power when large dust storms are present.

3.2. Laser Power Transmission System

The laser power transmission system is mainly driven by the receiver technology (photovoltaic for the visible, 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 other 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.

Most of the solid state lasers are based on crystal technology (Nd:Yag, Nd:Y2O3, 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).

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 fiber laser with optimised sun collector could be an interesting alternative, but no experimental results are yet available.

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 Fig 3.

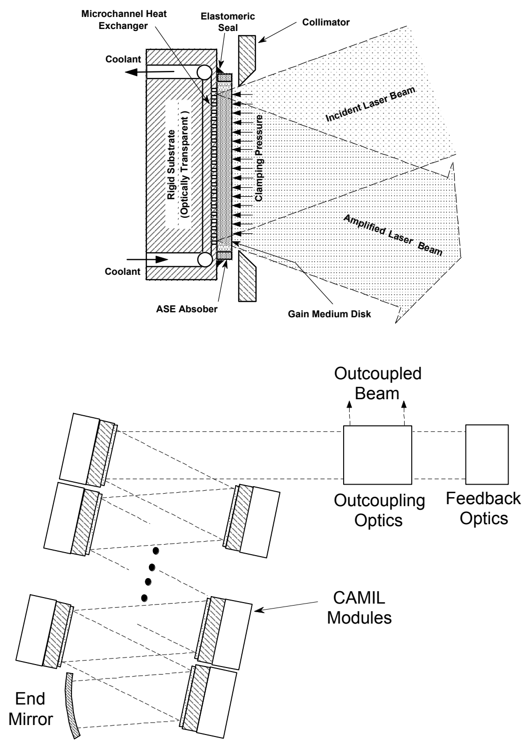


Figure 3: Laser system configuration

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.

In the IR domain, the CO_2 laser is an 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.

4. REVIEW OF APPLICATIONS

4.1- Range 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.

Power to GEO 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.

Power to interplanetary vehicles

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 and representing an array of 150 m diameter provides 1.2kW at user level, assuming a receiver surface of 1000 m^2.

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.

Application to Darwin mission

The utilisation of the SPS concept for the Darwin mission (Fig 4) 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.

It includes a laser power transmission system that provides power (1.5 kW) to each of the free flyers. The proposed fibered laser diode is an existing equipment (0,808 µm wavelength, multimode fiber coupled with 1mm fiber core) which can be space qualified. The emitter diameter is 0.2m and the pointing accuracy (1.1mrad) is easily achieved. The emitted power is 4 kW and 2.24 kW would be available at the user level. For the complete constellation, about 300m^2 of solar cells have to be installed on the solar sail. The laser transmission system technology is already existing and space qualified.

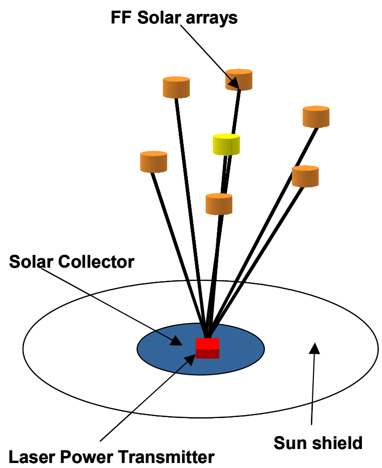


Figure 4: Darwin alternative concept

4.2- 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 limited to a maximum diameter 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 in an areo-synchronous orbit (17 000 km altitude in the Mars equatorial plane). It will face some short eclipses around equinoxes, and will remain permanently in visibility of the rover.

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). Consequently, for this application the SPS is based on laser power transmission with photovoltaic cells on the rover.

A key issue for laser transmission is the occurrence of dust storms. In that case, it is assumed that the rover receiver surface collects enough energy for its dormant mode, 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.

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 small laser beacon or corner cube has to be implemented on the rover to support the rover position acquisition process. Each telescope is actively controlled to achieve the fine pointing requirement. The rover receiver surface is equipped with optimised solar photovoltaic cells for 1.06µm, 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 Fig 5. 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 about 41t for a diameter of 5m. It is launched into LEO and transferred to Mars with its electric propulsion system.

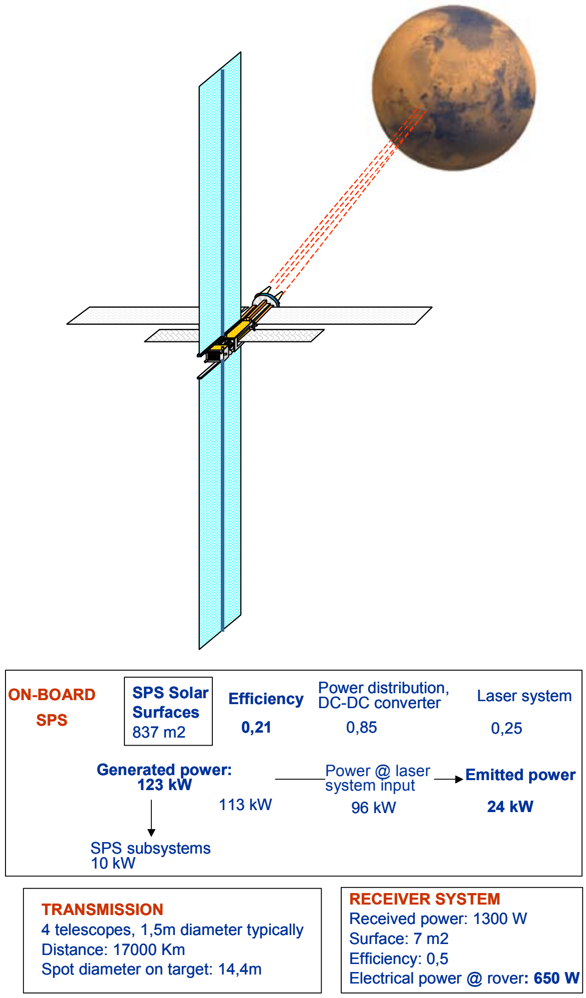


Figure 5: SPS system concept and performances

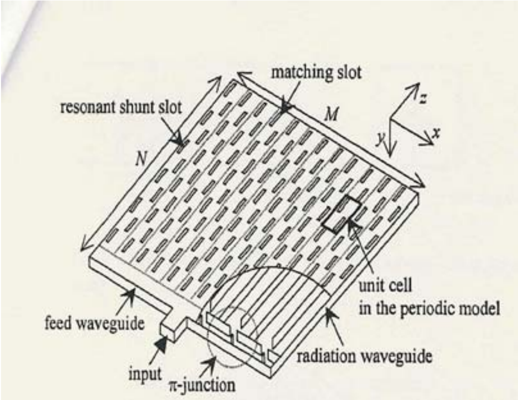
4.3- Power delivery to Mars base

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 could be located at a safe distance of the Mars base.

The SPS is preferably located in areo-synchronous orbit, at 17 000 km altitude in the Mars equatorial plane. RF power transmission is preferred, because size constraints on the receiver can be somewhat relaxed for this application while laser transmission is still penalised in case of dust storms.

RF power transmission system

The receiver system will be composed of rectennae. Several types of rectenna have been defined, all based on current technology state-of-the-art. A low power



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 6: Rectenna technology and dimensions

density rectenna has been selected to minimize the on-board projecting antenna sizing. Each rectenna is a metallised foam flat waveguide slot array. Fig. 6 illustrates a rectenna element and its sizing features.

The proposed transmitting system includes 100 W TWT/EPC modules and a 132m diameter slot array antenna. There are 26 680 modules, each with a size of 0.7mx0.7mx0.03m. A retrodirective phase conjugation circuit ensures the adequate beam pointing of the arrays towards the rectenna. The RF projected power is 2 MW. The average power density at transmitting area is 146W/m^2 with a maximum of 374W/m^2 in the centre. Fig 7 illustrates the slot array technology.

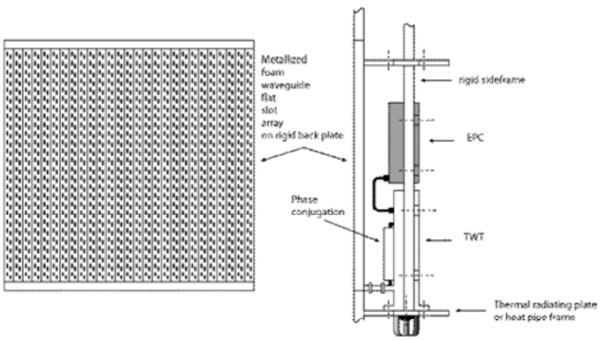


Figure 7: On board slot array antenna technology

SPS system concept

The power generation is ensured by solar cell surfaces (more than 42 000 m^2) 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 (see Fig 8), 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 m^2) and an active thermal loop. The SPS concept with the slot array antenna includes a large flat antenna (132m) mounted on a central core.

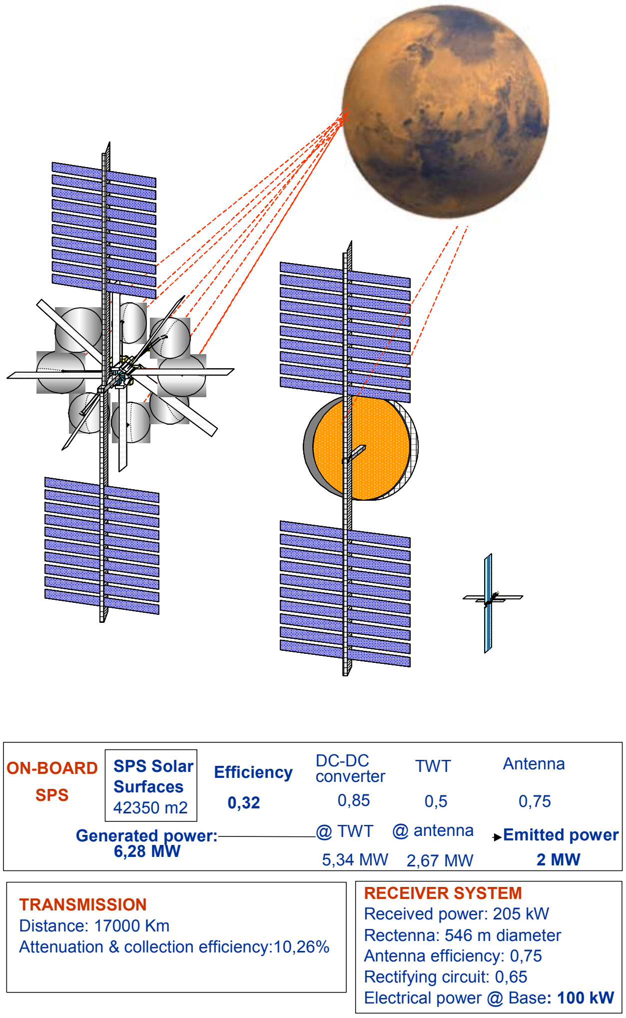


Figure 8: SPS system concepts and performances for Mars base

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 Fig 8. 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.

4.4. Power delivery to Moon infrastructure

The power required for a Moon infrastructure is a few tens of kW, permanently. 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. The SPS includes independent power systems and the radiator surfaces are mounted on the back of the antenna structure. 5000m^2 of solar surfaces are installed generating up to 2 MW. 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 Fig 9. An illustration of the SPS is given on Fig. 11.

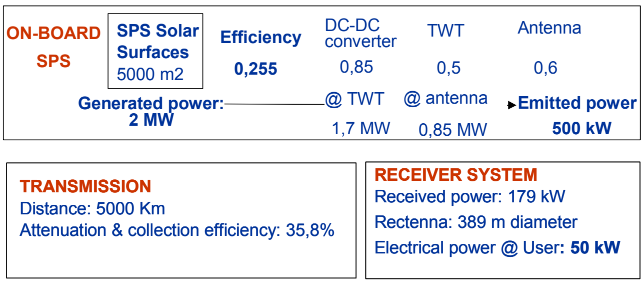


Figure 9: Performances of RF based SPS

Laser based SPS system

The laser based SPS would be located in Earth-Moon Lagrangian 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%. Fig 10 recalls the SPS system performances.

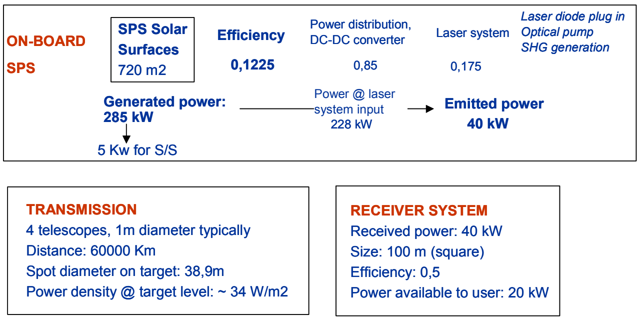


Figure 10: Performances of laser based SPS

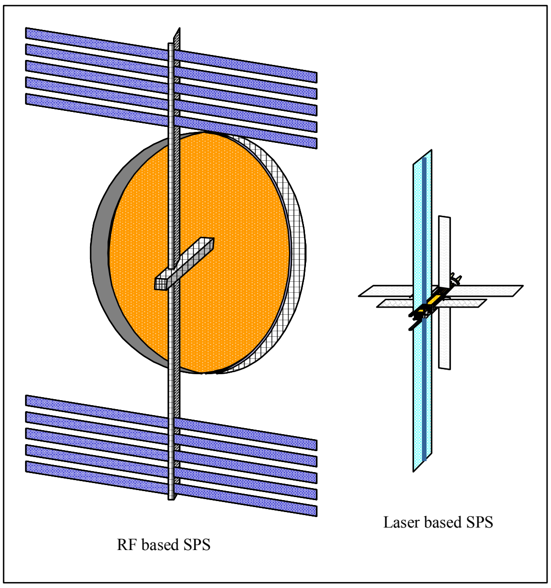


Figure 11: Illustration of SPS concepts

5- 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. This leads to overall system efficiencies of a few percent, and to important SPS masses. This concept evaluation assumes an electrical propulsion system ensuring the SPS transfer from LEO to its final positioning. In the case of a laser transmission system, the SPS is compatible with a single launch (with a possibly heavy launcher) in LEO.

This preliminary evaluation is a basis to identify the critical issues driving the performances and the technology improvements to drastically reduce SPS mass down to more competitive values. Thus, in the RF case, the signal generator technologies could be improved for 35GHz in terms of efficiency and mass; likewise, the rectenna elements could be optimised for the application. On the laser system side, new technologies like solar pumped laser, or new types of fiber laser have the potential to significantly improve the on-board efficiency. Such an increase of the overall efficiency has a direct drastic impact on the SPS mass.

In parallel, new or improved technologies for large solar surfaces, heat dissipation, deployable structures would reduce the SPS size.

Finally, the optimisation of the SPS system (SPS and target) should take into account these areas of improvement for the balance between target surface and SPS transmitter and mass. This drives the choice of key parameters, such as the RF frequency, as a function of critical issues like e.g. mass and pointing accuracy.

Therefore, there is a high potential of improvement for the SPS system from the concept presented in this preliminary evaluation, which makes it an attractive solution for these kinds of applications.

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