IAC-04-R-3-06

SOLAR POWER SATELLITES FOR SPACE APPLICATIONS

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ABSTRACT

The Solar Power Satellite (SPS) system is a candidate solution to deliver power to space vehicles or to elements on planetary surfaces. It relies on RF or laser power transmitting systems, depending on the type of application and relevant constraints.

The SPS system is characterized by the frequency of the power beam, its overall efficiency and mass. It is driven by user needs and SPS location relative to the user.

Several wavelengths can be considered for laser transmission systems. The visible and near infrared spectrum, allowing the use of photovoltaic cells as receiver surface, has been retained. Different frequencies can be used for the RF transmission system. The 35 GHz frequency has been considered as a good compromise between transmission efficiency and available component performances.

The utilisation of the SPS to deliver power to small rovers or human outpost on Mars, and to an infrastructure on the Moon allows to assess different drivers in terms of user needs, receiver surface, distance between SPS and target, and to perform a preliminary sizing, based on current or reasonably achievable technologies, with respect to different sets of constraints. The SPS system appears as an attractive solution for these applications. The use of advanced or new technologies would drastically lower mass and increase the performances of the SPS system.

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, 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 high power levels may be needed. Large infrastructures on the 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 planetary surfaces.

Studies have been carried out for many years on the problem of providing renewable electrical energy from space to Earth with SPS. Recently, an ESA funded study, led by EADS Astrium with the support of the University of La Réunion assessed the utilisation of SPS concepts for space-to-space and space-to-planet applications. This paper reviews the main results of this study for the SPS power delivery to elements on Mars and Moon.

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 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 of the power transmission system and the SPS position, driving the SPS-to-target distance and the sun visibility.

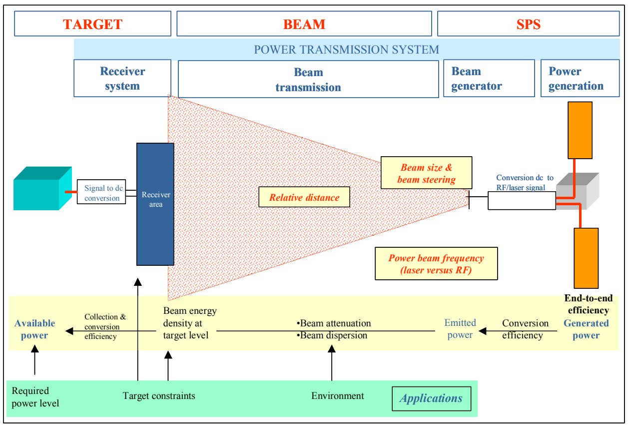


Figure 1: SPS system overview

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.

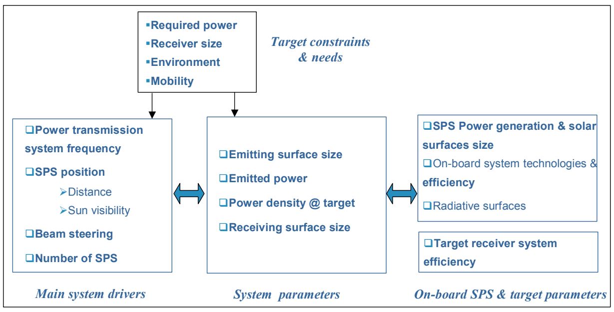


Figure 2: System key parameters

3. SPS APPLICATIONS

Several types of SPS missions have been reviewed, for delivering power to satellites or space vehicles as well as to elements on Mars or on the Moon surfaces. These latter applications are closer to the delivery of power from space to Earth. The power generation for these elements is a critical point due to either the environment (Mars case) or the long eclipse duration (Moon case). In the Mars case, two different applications have been assessed: delivery of power to a small rover, with small power needs, but very small receiver surface, and to a Mars base with large power needs, but freedom on the receiver surface.

There are some main differences in the system drivers between the space-to-planet and space-to-Earth applications. The first is the required power: up to 100kW for planets, in order of GW for Earth. Receiver surfaces on planets shall be minimised, either constrained by the target itself, or due to their implementation on the planet surface. Environment is also different: solar flux density around Mars is much lower than on Earth, atmosphere attenuation is different between Mars and Earth.

4. POWER DELIVERY TO ROVER ON MARS

4.1- System drivers

User needs and constraints

The objective is to permanently provide power to a small rover on the Mars surface. The rover is assumed operating in an area of 400 km diameter. It 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

The SPS is preferably located in an areo-synchronous orbit (17000 km altitude in the Mars equatorial plane). The distance to target will slightly increase (up to 20600 km) with the latitude of the target. The SPS will face some short eclipses around equinoxes, and will remain permanently in visibility of the rover. Positioning the SPS in low Mars orbit would result in a very low availability (a few % of time).

Power transmission system

At that distance, an RF power transmission is strongly penalised by the small size of the target. Consequently, for this application a laser power transmission is preferred.

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.

4.2. Laser power transmission system

Technology aspects

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 diffraction limited beam. The emitting optics diameter could be as large as possible to reduce the required emitting power, but is limited by the integration constraints. Future technology for large telescopes is 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 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). However, 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.

Application to rover

For this application, a solid state (Nd:Yag) diode pumped laser has been preferred, as it is an existing technology. 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.

The proposed power transmission system is composed of 4 independent laser systems, mounted on the same SPS, 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.

4.3. SPS system concept

The SPS system is illustrated in Fig 3. 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 is in order of 40t for a diameter of 5m. It is launched into LEO and transferred to Mars with its electric propulsion system.

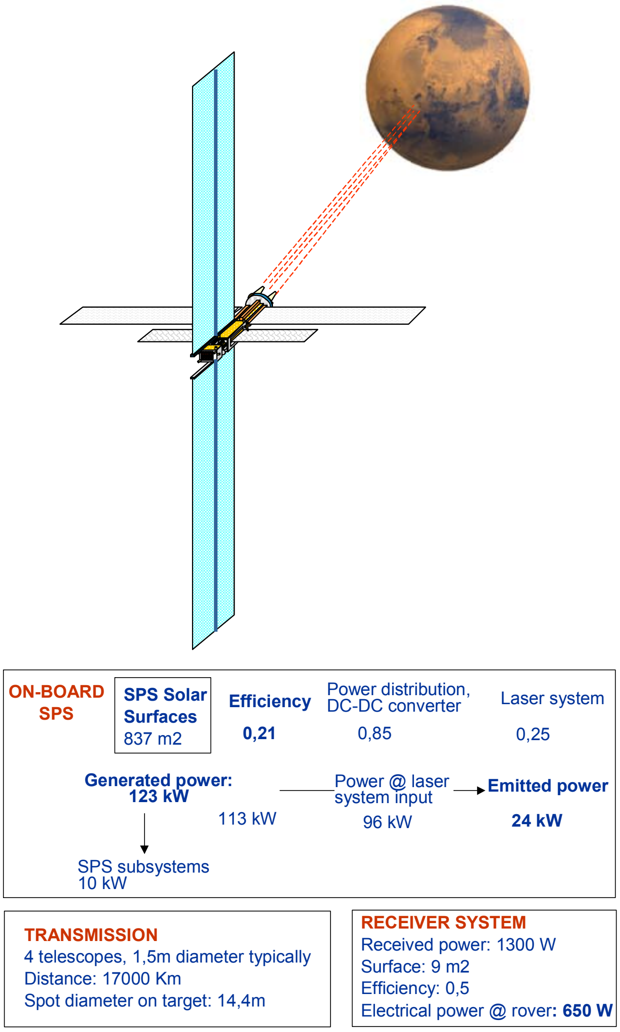


Figure 3: SPS system concept and performances

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)

5- POWER DELIVERY TO MARS BASE

5.1. System drivers

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.

5.2. RF power transmission system

Technology aspects

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 (emitting antenna and signal generator), the key driver being the transmission frequency. 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, the gain or effective area of the associated antenna and the efficiency of the antenna. From that, 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, then to derive the emitting system diameter and total emitted 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 approach is subsequently modified in case 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 a 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 and their ITU related availability. In case of power beaming to the surface of Mars, recent work demonstrated that the Martian atmosphere is usually much more transparent to RF than the Earth atmosphere and gave estimations for different window 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 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.

Application to Mars base

The receiver system will be composed of rectennae. Several types of rectennae have been defined, all based on current state-of-the-art technology. A low power density rectenna has been selected to minimize the on-board emitting antenna size. Each rectenna is a metallised foam flat waveguide slot array. Fig. 4 gives an example of its sizing features.

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: Example of rectenna dimensions

The proposed transmitting system includes 100 W TWT/EPC modules and a 132m diameter antenna constructed from slot antenna arrays. There are 26680 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 emitted 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 5 illustrates the slot array antenna on-board assembly.

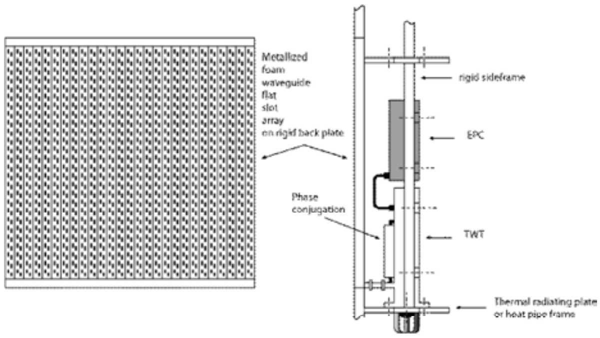


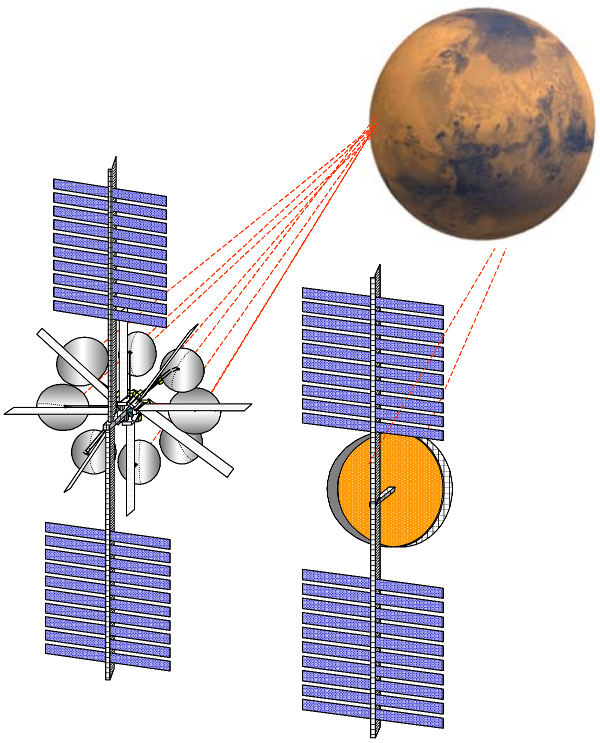
Figure 5: Illustration of on board slot array antenna

5.3. SPS system concept

The power generation is ensured by solar cell surfaces (more than 42000 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 (Fig 6) have been defined; they depend on the type of antenna. The concept with parabolic antenna comprises eight modules around a central core. Each 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. A primary reflector is mounted in front of the central core.

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 electronics, communications and electrical propulsion, and supports the two solar arrays trusses.



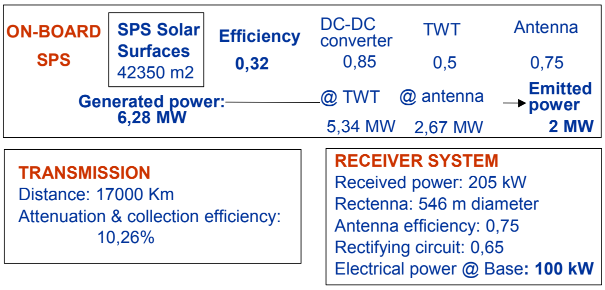


Figure 6: SPS system concepts and performances for Mars base

The SPS system performance is summarized in Fig 6. The overall system efficiency is about 1,6% and the SPS mass at launch is in the order of 500 tons. The SPS is assembled in LEO, and then transferred to Mars orbit with its electric propulsion system.

6. POWER DELIVERY TO MOON ELEMENT

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.

6.1. 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 generates 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 at launch is in order of 180t. The overall system efficiency is about 2.5%. The system performances are recalled on Fig 7. An illustration of the SPS is given on Fig. 9.

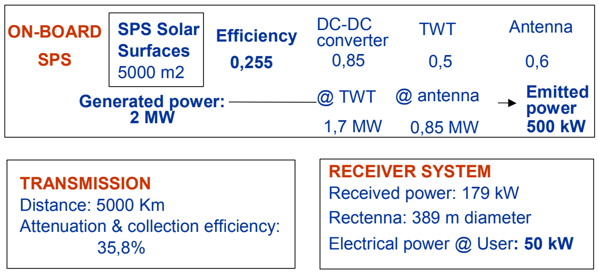


Figure 7: Performances of RF based SPS

6.2. Laser based SPS system

The laser based SPS would be located in Earth-Moon Lagrangian point L1 or L2, as function of target implementation, at a distance of about 58000 km from the target. It could provide a permanent illumination of any spot on 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 at launch and the overall system efficiency around 7,1%. Fig 8 recalls the SPS system performances.

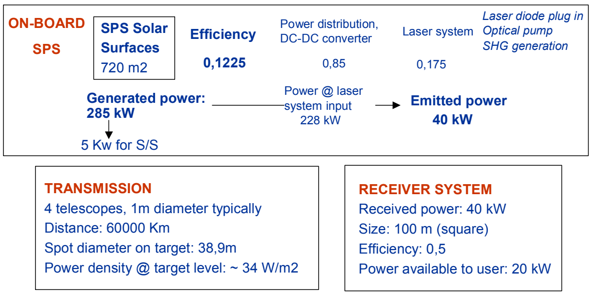


Figure 8: Performances of laser based SPS

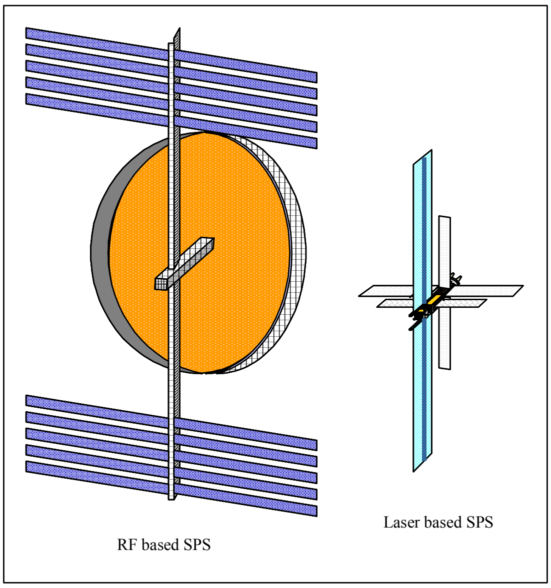


Figure 9: Illustration of SPS concepts

7- 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 today's only alternative to nuclear power sources.

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. In that way, several axes of improvement can be identified. A first one is the utilisation of advanced or new technologies for power transmission system. 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, propulsion, would reduce the SPS size.

The optimisation of the SPS system (SPS and target) should ensure an adequate balance between target surface and SPS transmitter and mass on one part, mass in orbit and mass on the surface on another part. 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.

Finally, SPS concepts alternative to the large platforms can be considered, such as the utilisation of a network of satellites, offering a larger virtual emitting diameter.

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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