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# Solar Power Satellites for Lunar Rover Exploration

**Rohan Ramasamy**
Advanced Concepts Team, European Space Research and Technology Centre, Keplerlaan 1, 2201 AZ, Noordwijk, Netherlands, rohan.ramasamy@esa.int
**Darian van Paridon**,
Faculty of Aerospace Engineering, TU Delft, Kluyverweg 1, 2629 HS, Delft, Netherlands, d.j.vanparidon-1@student.tudelft.nl
**Leopold Summerer**
Advanced Concepts Team, European Space Research and Technology Centre, Keplerlaan 1, 2201 AZ, Noordwijk, Netherlands, leopold.summerer@esa.int

**Abstract**

Solar power satellites have been investigated over the past fifty years as a sustainable solution to meeting global energy demand. However, the construction of a commercial solar power satellite, while in principle technically feasible, remains a long term goal, mainly due to the associated high economic cost and upfront investment. At the same time, there is a need for the development of suitable power generation technologies for lunar rover exploration missions to assess resources for future industries. These applications constitute a nearer term, intermediate goal due to their orders of magnitude lower power requirements.

The present paper builds upon previous studies of lunar solar power satellite concepts, focusing specifically on the optimisation of the orbit, and different system components for low power applications on the surface of the Moon. The performance of different solar power satellite systems is modelled to assess their potential to enable longer term, lunar rover exploration missions that survive the lunar night. If sub-microradian pointing accuracies can be achieved, conceptual designs exist that could support multiple rovers with a laser power in the range of a few kilowatts.

## Acronyms

**GaAs** gallium arsenide

**GEO** geostationary orbit

**LEO** low earth orbit

**PV** photovoltaic

**SPS** solar power satellite

**STK** systems tool kit

**WPT** wireless power transmission

## 1. Introduction

The development of lunar activities has been proposed as the next step in space exploration, due to its scientific value, and potential to launch a new cis-lunar space economy [1, 2]. While the development of a first human outpost is likely to be near the lunar poles due to better illumination conditions, previous studies have shown that global accessibility is necessary to maximise scientific and economic return [3, 4].

To support future, long duration lunar surface missions, effective power generation systems need to be developed. In addition, the early stage of future lunar exploration would be facilitated by lightweight solutions that can improve the versatility, and reduce the cost and risk of early missions. Most missions and future concept studies to the lunar surface have been based on the use of either solar or nuclear power systems, depending on the site and mission requirements [5].

Solar power Satellites (SPS) have been proposed as an alternative solution to nuclear power sources in enabling lunar bases to survive the lunar night [6, 7]. A SPS consists of an orbiting solar powered transmitter, commonly beaming in the microwave, or optical range, transmitting power wirelessly to remote users. These users could be anywhere on the lunar surface in line-of-sight of the satellite, making such a power system versatile and generically adaptable to many different use case scenarios and user requirements.

After being proposed in 1968 by Peter Glaser in the form of an engineering concept [8], some of the first experiments to achieve wireless power transmission (WPT) links were carried out by William Brown [9, 10]. Recent

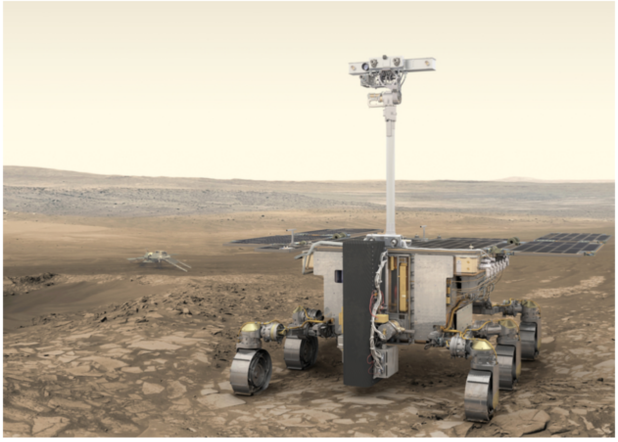

Figure 1: Artist's impression of the next generation ExoMars 2020 rover (courtesy of ESA ATG MediaLab). For a solar powered rover to be designed for the lunar environment, without reliance on nuclear technologies, a solution needs to be found for surviving the 14 day lunar night.

studies have outlined the potential value of SPS to the space sector [11]. Studies on the terrestrial applications of SPS have culminated in the general consensus that, while SPS would be technically feasible, most scenarios were economically challenging or impractical compared to alternatives [12].

The situation regarding the application of SPS for supplying power to in-space users is governed by a different set of evaluation parameters, including especially the additional versatility that such concepts offer. Brandhorst et al. carried out several studies to explore large scale, lunar SPS concepts. Their work outlines the performance of a power transmission link consisting of an orbiting satellite, transmitting 40 $kW$ to a lunar site with a 62 $m^2$ receiver on the lunar surface [13, 14]. The results show the potential to significantly reduce blackout times, achieving almost continuous coverage with small SPS constellations. A recent study also supports the possibility of applying SPS to facilitate Moon village concepts [15]. It remains unclear whether for high power levels, and large-scale users, investment in less versatile, but higher efficiency nuclear solutions would be advantageous.

Space start-ups have begun to develop compact, lightweight lunar rovers for exploring the lunar surface in search of resources, largely triggered by the launch of the Google X prize [16]. None of these mission concepts based near the equatorial plane are designed to survive the lunar night. The power requirements for such rovers to hibernate are in the order of 10 $W$ [17]. The use of SPS has been proposed for powering rovers in the past [11], but never for such lightweight lunar rover concepts. Next generation solar powered rover designs, following the state-of-the-art ExoMars 2020 rover (see Fig. 1), might also benefit from additional energy provided via such a WPT system. It could furthermore lower or remove the dependence of long-term, early stage lunar exploration on nuclear power systems.

The versatility of a SPS energy service provider could be particularly interesting during the early phase of lunar development, where lightweight, low cost rover exploration missions need to be developed to characterise the lunar surface, and its resources. This paper presents a preliminary analysis of lunar SPS links between orbiting satellites and a remote user on the surface of the Moon. The study focuses on the design of SPS systems that are delivering relatively low power levels, in the range of 10 $W$ to 1000 $W$, to small scale users on the lunar surface.

In Section 2, the necessary theoretical background to designing WPT links for the Moon is discussed, based on which the parameter space of orbital simulations will be determined. The methods used to model orbits with systems tool kit (STK) are outlined in Section 3. The results for SPS orbits around the Moon are then presented in Section 4. In Section 5, the viability of a SPS energy service provider concept for the Moon is discussed, and the conclusions, and further work from this study are provided in Section 6.

## 2. Theoretical design of a power transmission link

The performance of a SPS power transmission link can be approximated by modeling it similarly to a communication link, using the link performance equation [18]. For this study, the performance equation for a power transmission link is written as

$$P_r = \eta_{link}\eta_r P_t, \tag{1}$$

where $P_r$ is the received power, $P_t$ is the transmitted power by the SPS, and $\eta_{link}$ and $\eta_r$ are the link and receiver efficiency, respectively. The satellite efficiency terms are omitted as the focus of this study is not the design of the SPS itself. Instead, the transmitted laser power is restricted to levels considered achievable by current and near term technologies, as discussed in Section 2.6.

In this section, an initial assessment of the above terms will be given to characterise the SPS system. In addition, several other properties need to be assessed. These include the required pointing accuracy to ensure that the transmitted beam will hit the target, the required storage of energy on the receiver, and the laser wavelength of the transmitter. Each of these issues will be discussed below alongside terms in the power transmission equation for defining the performance of the link.

The following analysis is restricted to optical wireless power transmission systems. The reason that microwave systems are not suitable for the considered application is discussed in Section 2.7.

### 2.1 Rover design and power requirements - $P_{in}$

The required power at the receiver will depend on the rover design. We consider two designs taken from specifications of the Sorato and AMALIA rovers (as shown in Table 1). These designs are used as representative examples of lightweight specifications for 'new-space' solar powered lunar rovers, though the two rovers differ significantly.

For the Sorato rover, the power requirements for hibernation, $P_{hibernation}$, and operation, $P_{operation}$, are taken to be $4.5\ W$ and $21.5\ W$. These values correspond to when the rover is idle, and operating in variable terrain conditions, respectively [19]. For the AMALIA rover, the hibernation and operation power are $7.2\ W$ and $100\ W$, corresponding to the heating requirements for the rover without incident light from the sun, and its maximum power [17]. The battery capacity, $E_{battery}$, is $38\ Whr$ for the Sorato rover and $100\ Whr$ for the AMALIA rover.

### 2.2 Rover receiver efficiency - $\eta_r$

The chosen photovoltaic (PV) receiver needs to have a high efficiency for both the solar spectrum, and monochromatic light at the wavelength emitted by the laser on the satellite. For broadband sunlight, the efficiency is assumed to be low because the cells will be optimised for monochromatic conversion. As a result, they are expected to perform worse than conventional space solar cells when exposed to the solar spectrum. A $20\ \%$ receiver efficiency is assumed, similar to values used in previous studies using gallium arsenide (GaAs) cells [14].

Monochromatic PV cells have been developed for low, and high power applications [20, 21, 22], but power levels for terrestrial non-military applications are currently below $1\ W$. Efficiency levels above $50\ \%$ have been reported for GaAs laser concepts [23]. The assumed maximum efficiency of the receiver is limited to $50\ \%$ for this assessment.

#### 2.2.1 Receiver area and surface flux

The receiver area, $A_r$, (as shown in Table 1) for the rovers has been calculated based on the necessary area to generate the active power requirements in sunlight (solar flux of $1367.0\ Wm^{-2}$) and the estimated receiver efficiency for the rover.

When powered by the satellite, the necessary transmitted power incident on the receiver is between $9\ W$ and $200\ W$, depending on the targeted rover specifications, and operational mode. The required surface flux on the Moon depends on the receiver area of the targeted rover, and varies from approximately $39.3\ Wm^{-2}$ to $546.4\ Wm^{-2}$ for the cases studied. Despite its lower power requirements, the minimum surface flux is not set by the Sorato rover, because of its much smaller assumed receiver size.

#### 2.2.2 Tracking losses

The analysis in this study does not take into account tracking losses due to angular misalignment of the receiver with the transmitted beam. For small rover systems, tracking capabilities are likely to be limited. The exact loss due to tracking depends on the detailed rover design, orbit of the satellite, and location of the rover on the Moon. For this initial study, the parameter space could not be explored fully, and so was omitted.

### 2.3 Link efficiency - $\eta_{link}$

The link efficiency is determined by the required pointing accuracy and beam spreading.

#### 2.3.1 Pointing accuracy

For power transmission applications, pointing errors must not prevent the necessary average power from being received. There is currently no established convention on the pointing requirements for a power transmission link. For small-scale applications, where the receiver is limited in terms of size, the transmitted beam will need to be larger than the receiver to ensure that power is transmitted continuously.

If the receiver is assumed to be circular (see Fig. 2), an estimate of the required radius of the beam is given by

$$w_b > \epsilon_p + w_r = z\sigma_p + w_r, \tag{2}$$

where $\epsilon_p$ is the error in offset distance of the beam at the target, $z$ is the transmission distance, and $\sigma_p$ is the error in pointing angle by the satellite, which is assumed to be small. $w_b$ and $w_r$ are the beam radius and receiver radius, respectively.

The above definition of the pointing accuracy constraint does not take into account the gaussian profile of the beam. This assumption is appropriate if the beam size is expected to be appreciably greater than the transmitter radius, such that the beam profile becomes more uniform.

Optical pointing systems for proposed low earth orbit (LEO) and geostationary orbit (GEO) SPS concepts have ambitious pointing accuracies for large optical systems, in the range of $0.1$ to $1\ \mu Rad$ [24]. A SPS application powering rovers from areosynchronous orbit has previously been proposed with a $89.2\ nRad$ pointing accuracy [11]. In this study, $0.1$ to $1\ \mu Rad$ pointing accuracies are considered.

Table 1: Specifications of different rover designs. The receiver areas are calculated from the power requirements and assumed receiver efficiencies in this study [17, 19].

| | $P_{operation}$ $(W)$ | $P_{hibernation}$ $(W)$ | $E_{battery}$ $(Whr)$ | $A_r$ $(m^2)$ | Mass $(kg)$ |
|---|---|---|---|---|---|
| Sorato | 21.5 | 4.5 | 38.0 | 0.079 | 3.8 |
| AMALIA | 100.0 | 7.2 | 100.0 | 0.366 | 30.9 |

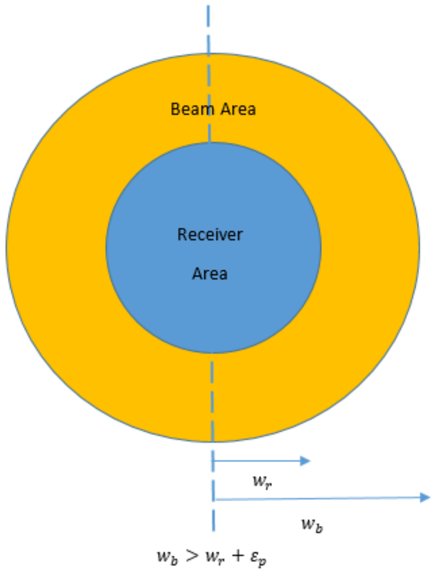


Figure 2: Diagram showing an estimate for the required pointing accuracy for WPT to a remote target.

### 2.3.2 Maximum link efficiency

The maximum link efficiency is defined as:

$$\eta_{link\ max} = \frac{A_r}{A_b} = \frac{w_r^2}{(\sigma_p z + w_r)^2}, \qquad (3)$$

where $A_r$ and $A_b$ are the receiver, and beam area at the target, respectively. This equation is used to place a constraint on the area covered by the beam on the surface. Specifically, this surface beam area must be greater than $\frac{A_r}{\eta_{link\ max}}$.

The maximum link efficiency relationship (see Eq. 3) is plotted (see Fig. 3) to estimate the performance of transmission links for each rover, at the above pointing accuracies. The results show that the maximum link efficiency that can be achieved for small receivers is low at microradian pointing accuracies, only reaching 9 $\%$ for the AMALIA rover, at a 800 $km$ range. Sub-microradian pointing errors can achieve much higher efficiencies for the considered ranges.

Larger receivers achieve higher efficiencies as the error in alignment due to pointing inaccuracies becomes less significant. This indicates the importance of both

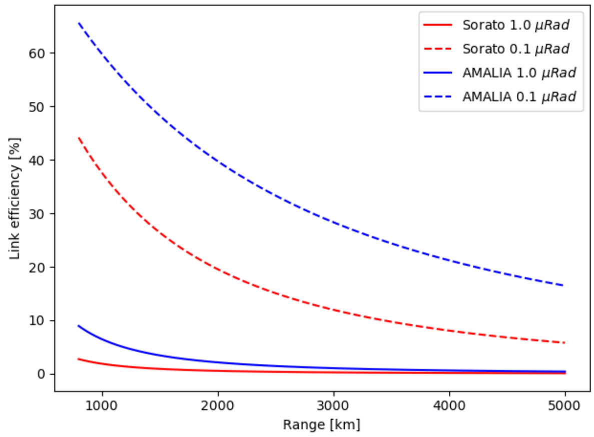


Figure 3: Plot of the maximum link efficiency achievable for each rover, assuming different pointing accuracies. These values set an upper bound on the achievable performance, according to the constraints defined for this study (see Eq. 2).

the pointing error and the receiver size in determining the performance of the link, and that as WPT applications increase in scale, their efficiency will increase as well.

## 2.4 Diffraction losses

The power requirements of a laser transmitter can be determined from the radius of the emitted gaussian beam. For a single laser, or an array using coherent side-by-side beam combining, the beam radius is given by

$$w_b(z, w_t) = w_t\sqrt{1 + \frac{z^2\lambda^2}{\pi^2 w_t^4}}, \qquad (4)$$

where $w_t$ is the transmitter radius, and $\lambda$ is the wavelength of light used. Conservation of energy can be used to get the received flux at the target for a given transmitter aperture and power at a given distance from the target.

Modern terrestrial SPS concepts make use of more advanced optics than gaussian beam divergence, which can reduce the beam spot size on target [25]. The transmitter physics used in this study should give a lower limit to the performance that can be achieved for the lunar SPS concepts considered.

### 2.5 Battery requirements for surviving blackouts

A single SPS is not able to provide continuous coverage to a lunar rover, because there will always be times when the satellite does not have a line-of-sight access to the target. As a result, the rover will need some battery storage capacity to sustain its operations during these periods. The required energy capacity can be approximated by

$$E_{battery} = P_{hibernation} T_{blackout}. \tag{5}$$

where $T_{blackout}$ is the length of the maximum blackout period.

The battery capacity will depend on the chosen orbit, and its associated maximum blackout period. This relationship will be used in the analysis of simulation results in Section 4.1.

### 2.6 Potential operating space for rover designs

Using the above equations, it is possible to calculate the link efficiency (see Eq. 3) of a laser power transmission link, subject to constraints on its performance. The received surface flux is constrained to be greater than the required flux to power the target rover. In addition, the modelled link must be able to transmit to the rover subject to the pointing requirements outlined above.

This model is applied to the Sorato rover at its operational power for different assumed pointing errors (see Fig. 4). The plots show the link efficiency of the system, given in percent on a logarithmic axis, as a function of transmitter radius, and transmission distance. Representative laser powers are considered to be 4.0, 15.0 and 100.0 $kW$. These powers were taken from terrestrial continuous power transmitters used in industry [26, 27]. 859 $nm$ laser transmitters optimised for GaAs cells have been proposed at these power levels for similar applications previously [13].

The blank spaces in these plots are designs which are not feasible subject to the pointing, and power requirement constraints. At small and large transmitter diameters, most of the design space is removed, because the power received is too low. The middle region of the parameter space, containing the highest efficiency designs, is removed due to the pointing accuracy requirements. The range of possible transmission distances increases as the power of the transmitter increases, because this enables the minimum power requirement to be achieved for a larger beam spot size.

Most link efficiencies in the feasible parameter space are below 10 %, and decay quickly to values below 2 % at ranges above 2000 $km$ for the 1 $\mu Rad$ case. With the performance of current laser transmitters using gaussian optics, and no beam focusing, the efficiency of SPS power transmission links is very low, leading to the need for transmitter powers above 15 $kW$ to access altitudes above 2500 $km$ for the Sorato rover. Higher efficiencies can be obtained with a more challenging 0.1 $\mu Rad$ pointing error. If this is achievable, a 4 $kW$ laser transmitter could provide operational power to the Sorato rover over most of the altitude range considered. Similar conclusions are reached for the AMALIA rover design.

### 2.7 Choice of wavelength

The above analysis has focused on gaussian beam optics applicable to laser systems. Typically, SPS concepts use either microwave, or optical frequencies. Microwave transmitters and receivers have not been considered in this study, because the spot size for microwave transmission concepts is over 1000 times greater than for laser transmitters, requiring significantly shorter ranges. As the simulation results discussed in Section 4 will show, these lower altitude orbits are less promising for SPS links due to longer blackout periods and increased transmission intermittency. For this reason, microwave wavelengths were omitted as a viable design option for this study.

## 3. Simulation methods

The following analysis uses the same methodology as previous studies, which model the orbits of SPS power transmission links using STK [13, 14]. An example of one of the simulations from this study is shown (see Fig. 5).

Orbital simulations around the Moon can be initialised with one or more satellites, modelling the access to targets located on the lunar surface. It is assumed that the speed at which the target moves, and the region across the Moon's surface which it explores, is small enough that the target can be approximated as stationary.

### 3.1 Modes of operation

A SPS link is defined to be in one of three states (see Fig. 6). The first state is when the rover has access to direct sunlight. In this instance, the rover supports itself using the sun, and the state of the SPS does not need to be taken into account. The second case is when the satellite is in view of the sun, while the target rover is eclipsed. This is defined as an active period, in which the satellite powers the rover. The final event type is a blackout event. This occurs when the rover is eclipsed, and the SPS cannot beam power to it. This may either be because the SPS has no access to the target, or is eclipsed itself.

### 3.2 Simulation analysis

Reports are generated in STK for the access periods of the satellite to the target, as well as the times at which the SPS and target are in sunlight. This information can be used to

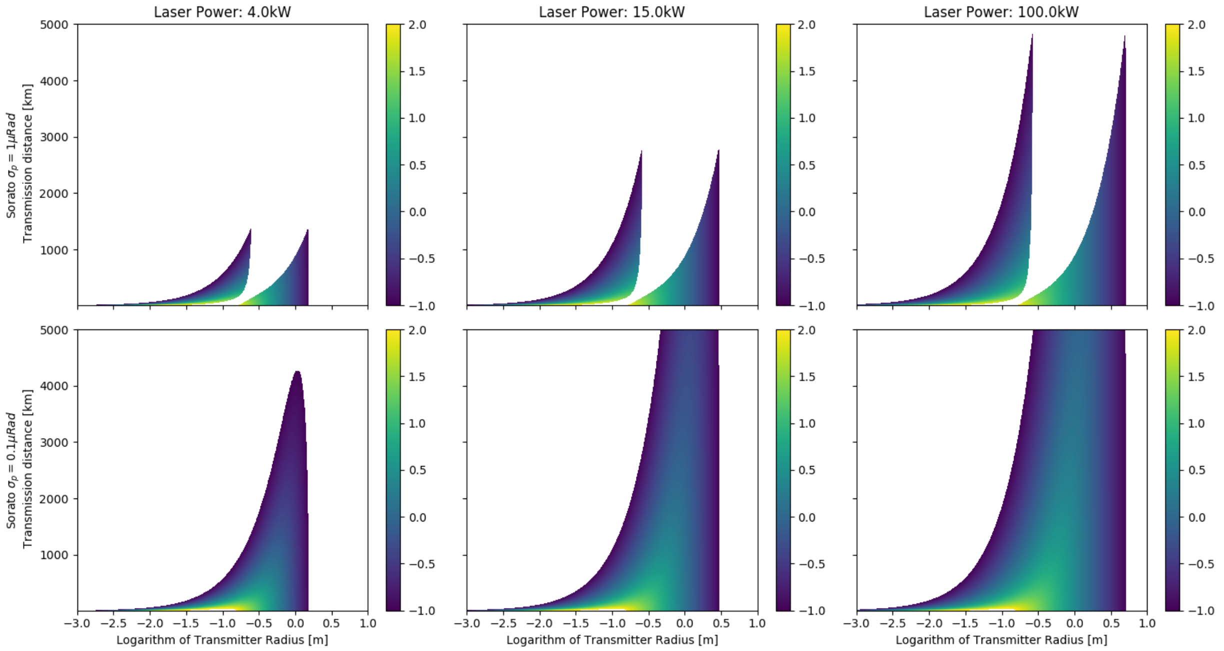


Figure 4: Link efficiency for the Sorato rover in operation mode assuming $1\ \mu Rad$ and $0.1\ \mu Rad$ pointing errors. The efficiency is plotted as a percentage on a logarithmic scale. A sub-microradian pointing error is necessary for high altitude Sorato link designs below $4\ kW$. The rover configurations modelled show that most of the feasible design space for such transmission links is at orbit altitudes below $5000\ km$.

work out the duration of active periods and blackouts for the power transmission links.

Statistical values are used for the range between the target and satellite, due to the large amount of data required to store the time varying range for all simulations. The average of the minimum and maximum range for all access periods are taken to give an indication of whether the pointing and power requirements for a particular link are met.

### 3.3 *Orbit propagator*

The J4 perturbation model is used to propagate the satellite orbit, taking into account effects due to the oblateness of the Moon. This propagator is appropriate for preliminary assessments of maintained satellite orbits where the maintenance manoeuvres are not modelled [28].

### 3.4 *Parameter space selection*

To assess the feasibility of different SPS designs, the performance of different orbits were compared when beaming to the same target, fixed at a latitude $45\quad N$. Simulations are run over a two year period from the $17^{th}$ May 2018. This ensures that fluctuations in results will average out over the simulation time span.

The parameter space for orbits is vast. Previous studies have shown the potential of both equatorial and polar orbits [13, 14]. An orbit with an inclination from the equatorial plane is limited in its ability to service both the Northern and Southern hemispheres of the Moon at any given time, which leads to long eclipse times. Highly elliptical polar orbits are designed to service only one hemisphere of the Moon.

For this study, orbits are constrained to the equatorial plane. In this plane, the semi-major axis and the eccentricity of the orbit are then varied to model circular and elliptical orbits in the range of perilunes and apolunes above $800\ km$ and below $5000\ km$. Lower altitude orbits are not considered because they have limited line-of-sight access for the selected target.

## 4. Results

### 4.1 *Assessment of power transmission links*

Potential orbits for SPS energy service providers can be found by applying a set of constraints to the data generated from STK simulations. These constraints are necessary, but not sufficient in determining the feasibility of the orbit, as is discussed further in Section 4.2.

The pointing and minimum power requirements are defined as in the preliminary analysis in Section 2.6. In addition, the maximum blackout duration can be used to apply

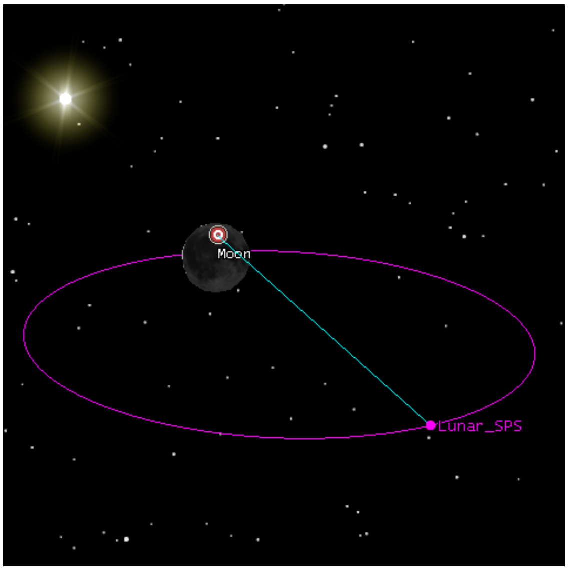


Figure 5: STK simulation modelling the link between a lunar SPS and a target on the Moon. The duration and sequence of active periods and blackouts is used alongside statistics on ranging to assess the performance of power transmission links.

Table 2: Table of constraints applied to simulation results. Orbits that satisfy these constraints define a parameter space for SPS designs.

| Constraint | Condition |
|---|---|
| Minimum power | $>= P_{operation}$ |
| Pointing accuracy | $w_b > z\sigma_p + w_r$ |
| Minimum active time | $> T_{eclipse}\frac{P_{hibernation}}{P_{operation}}$ |
| Maximum blackout time | $T_{blackout} = \frac{E_{battery}}{P_{hibernation}}$ |

a constraint on the necessary power storage (see Eq. 5), such that a single blackout is not able to deplete the rover battery capacity. The minimum overall active time of the SPS is also constrained to ensure enough energy is delivered to survive the lunar night. For this to be true, energy delivered during the active beaming time at operational power must be greater than the energy used by the rover in hibernation. $T_{eclipse}$ (as shown in Table 2) is the total time for which the target is eclipsed from the sun.

Within the feasible design space, the orbit is optimised to maximise the average link efficiency over the simulation. This optimisation metric is chosen because it provides the most flexibility in terms of transmitter power and the minimisation of the SPS system size overall. In general, the selected orbit, marked on the plot of mean link efficiency, will be at the lowest altitude orbit possible within the design space, as this will reduce the mean range between the target and satellite during the two year period.

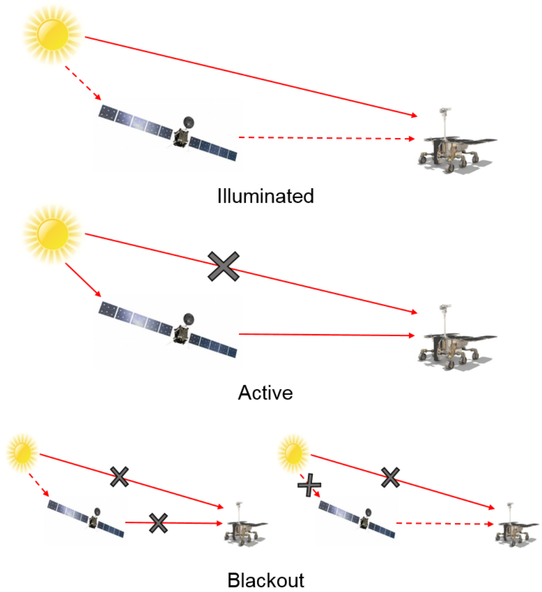


Figure 6: The satellite and target can be in one of three conditions. An illuminated state (top) is when the target is powered by direct sunlight, and the SPS is assumed to be inactive. An active period (middle) is when the SPS is actively beaming to the target. A blackout event (bottom) is when the SPS has no access to the target, or is eclipsed while in range, and the target is simultaneously eclipsed.

Results from simulations for the Sorato and AMALIA rovers are shown for $0.1\ \mu Rad$ pointing accuracy (see Fig. 7). The plots show the total active time as a percentage of the two year simulation, the maximum blackout time for the simulation, the approximate laser power required for the satellite, and the mean link efficiency achieved.

It can be seen that for both rovers, the lower altitude parameter space has been removed. This is due to the minimum active time and pointing requirement constraints. The high altitude parameter space has also been removed for the Sorato rover. This is due to the maximum blackout constraint. The AMALIA rover can function in these higher orbits because it has a larger battery capacity compared to its power requirements in hibernation.

At $0.1\ \mu Rad$, the power of the laser must be greater than approximately $3.44\ kW$ and $2.35\ kW$ for the Sorato and AMALIA rovers respectively at the optimum design point shown in the plots. The assumed AMALIA rover design has lower power requirements, despite its higher operation and hibernation power demand. This is because the assumed receiver area is much larger than that of the Sorato rover, making higher link efficiencies possible.

If the pointing error is increased to $1\ \mu Rad$, the model optimises the link to the same orbit, constrained to this altitude by the minimum active time of the satellite.

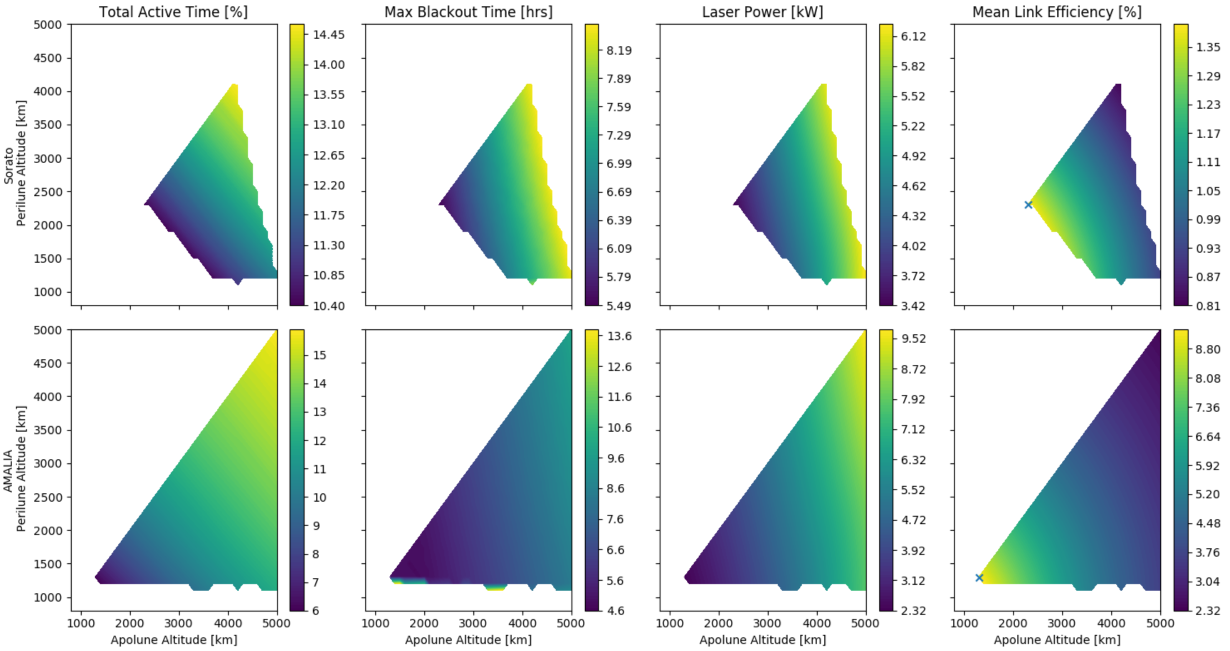


Figure 7: Plots of the performance of SPS links for the Sorato and AMALIA rovers assuming $0.1\ \mu Rad$ pointing accuracy. The optimum orbit, in terms of minimising the power requirements of the laser transmitter, is marked on the plots of mean link efficiency.

The laser powers increase substantially to $25.2\ kW$, and $14.2\ kW$, for the Sorato and AMALIA rovers, respectively. This power is on the same order of magnitude as the $40\ kW$ laser considered for the much larger scale lunar studies by Brandhorst et al. [13].

### *4.2 Energy balance during lunar night*

The results outlined above are not sufficient to confirm the achievement of indefinite rover operations. It is assumed in the assessment of the power storage constraint that the battery is fully charged at the beginning of the maximum blackout period. This may not be true, because the lunar night is 14 days long, and the maximum blackout duration is in the range of 5 to 14 hours (see Fig. 7). Multiple blackout periods will occur during each lunar night, for which the SPS will need to sustain the rover.

The energy stored on the Sorato, and AMALIA rovers is calculated over the duration of the simulation for their respective optimised orbits. During active periods, operational power is delivered to the rover, so that the battery is assumed to be charging with input power, $P_{operation}$ $P_{hibernation}$. During blackout periods, the rover is in hibernation mode.

It was found that both the AMALIA and Sorato rover batteries were depleted during each lunar night for the original optimised orbits considered above. Although the average power delivered to the rover is greater than the necessary power to survive the lunar night, the local energy demand at increased points of intermittency in the service provided by the SPS exceeds the battery capacity. The increased intermittency occurs because, during these periods, the SPS is in the shadow of the Moon for more of the time that it has line-of-sight access to the target.

The overall energy delivered to the rovers can be increased in three ways. The apolune and perilune altitude can be increased, a second SPS can be introduced, or it can be assumed that the SPS has its own battery, allowing it to store energy that it can beam to the rover, even when eclipsed. Because the detailed design of the SPS is left out of scope, the third option was not considered in this study.

Adjusting the satellite orbit for the AMALIA rover allowed it to survive the lunar night for a $1700\ km$ altitude, circular orbit. The change in altitude increased the power requirements to $2.8\ kW$ and $19.4\ kW$, depending on the pointing accuracy of the satellite.

The Sorato rover could not survive the lunar night by increasing the altitude of the satellite within the range of the design points considered in this study. Instead, a second satellite had to be introduced. The second SPS is placed in the same orbit, at a 180 argument of perigee to the first. This multiple satellite design is not optimised, but would allow the Sorato rover to survive the lunar night.

The above adjustments to the orbits lead to a surplus of

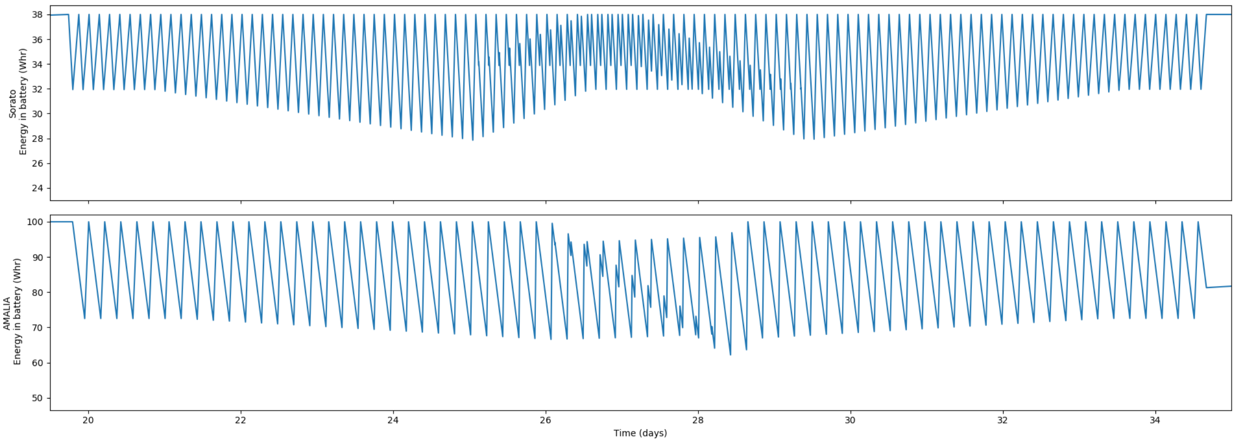


Figure 8: Energy stored by the Sorato and AMALIA rover batteries over one lunar night for their chosen orbits (as shown in Table 3). The energy delivered to the rover, decreases for the middle period of the night, because the SPS is prevented from beaming, while in the shadow of the Moon.

energy delivered to the rovers that enables them to operate for $26.4$ % and $10.3$ % of the lunar night for the Sorato and AMALIA rovers, respectively. Alternatively, the active time used to beam this excess energy could be used to service other targets. The minimum battery capacity over the two year simulation period is $61.7$ % for Sorato and $47.4$ % for AMALIA.

## 5. Discussion

The designs considered in this study have low link efficiencies, which lead to considerable power requirements on the laser transmitters relative to the receiver operating power. The power required for Sorato and AMALIA concepts would need to be above $3.44\ kW$ to $25.2\ kW$ and $2.8\ kW$ to $19.4\ kW$, respectively, depending on the pointing accuracy assumed (as shown in Table 3).

Subject to the constraints assumed in this study, it is possible to enable lightweight lunar rover missions that can survive the lunar night using SPS technologies. These SPS systems would have power levels similar to modern terrestrial lasers, and could provide a global lunar power supply for the early stage exploration that is necessary to evaluate the resources of the Moon.

At the same time, this study has highlighted the challenges posed to a lunar SPS energy service provider. It has been shown that the mean link efficiency for small targets at the ranges being considered is very low for near term system designs. Larger users can achieve a higher efficiency. In general, it can be said that as the scale of lunar exploration and industries increases, the performance of a SPS energy service provider will also increase.

There are several ways in which the performance of small scale exploration could be improved. The critical design parameters are the pointing accuracy of the power transmission link and receiver area. It has already been shown that reducing the pointing error to $0.1\ \mu Rad$ reduces the necessary laser power.

Table 3: Design parameters of SPS links for the Sorato and AMALIA rover to survive the lunar night.

| Parameter | Sorato | | AMALIA | |
|---|---|---|---|---|
| Number of Satellites | 2 | | 1 | |
| Apolune altitude ($km$) | 2300.0 | | 1700.0 | |
| Perilune altitude ($km$) | 2300.0 | | 1700.0 | |
| $\sigma_p$ ($\mu Rad$) | 0.1 | 1 | 0.1 | 1 |
| $\bar{\eta}_{link}$ (%) | 1.40 | 0.21 | 7.92 | 1.25 |
| $P_t$ ($kW$) | 3.44 | 25.2 | 2.8 | 19.4 |
| $w_t$ ($m$) | 0.95 | 0.26 | 0.86 | 0.24 |
| $E_{battery\ min}$ (%) | 61.7 | | 47.4 | |
| SPS Active time (%) | 5.21 | | 3.51 | |

To achieve a larger receiver area, the SPS could power a lander. Exploring rovers could use the lander as a base to receive power, allowing them to survive the lunar night. Alternatively, as shown for the Sorato rover, a relatively small SPS constellation would increase the power delivered, and reduce the intermittency to a single target on the Moon. Having more satellites would enable lower altitude orbits. This would in turn reduce the power level of the necessary laser, and improve the link efficiency.

The average active time per satellite for the SPS links modelled in this study is $3.51$ $5.2$ % of the two year simulation time (as shown in Table 3). This indicates the potential for having many more target receivers on the Moon to extract more value from a single satellite.

## 6. Conclusion

This study has explored the potential of a SPS energy service provider to enable small scale lunar rover missions that survive the lunar night. This is a near term application of WPT that provides added value to the early stages of lunar exploration, in a way that should be scalable to larger investments at later stages in the timeline.

It is possible for SPS to provide a versatile power supply to multiple locations on the Moon at once, enabling long term access to these regions, and operation during the lunar night without using nuclear technologies. The value of this global access needs to be weighed against the power requirements to enable the technology.

The above model can be extended to include polar orbits and SPS constellations. Larger scale target receivers and improved optics should also be considered to increase the performance of power transmission links. More constraints concerning the tracking of the SPS by the receiver, the cost of station keeping, and the thermal management of both the SPS and receiver are necessary for the above modelling to give a comprehensive design of SPS systems. These topics are the subject of future work.

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## References

[1] J. Woerner and B. Foing. The "Moon Village" concept and initiative. *Annual Meeting of the Lunar Exploration Analysis Group*, 2016.

[2] I. Crawford. Why we should build a Moon Village. *Astronomy & Geophysics*, 58, 2017.

[3] D.B.J. Bussey, J.A. McGovern, P.D. Spudis, C.D. Neish, H. Noda, Y. Ishihara, and S.-A. Sørensen. Illumination conditions of the south pole of the Moon derived using Kaguya topography. *Icarus*, 208, 2010.

[4] G. J. Taylor and P. D. Spudis. Geoscience and a Lunar Base: A Comprehensive Plan for Lunar Exploration. In *Proceedings of a workshop sponsored by the National Aeronautics and Space Administration*, 1988.

[5] P. Eckart. *The Lunar Base Handbook*. Learning Solutions, 2006.

[6] L. Summerer, M. Ayre, A. Galvez, F. Ongaro, and M. Vasile. Roles of Solar Power from Space for Europe: Space Exploration and Combinations with Terrestrial Solar Power Plant Concepts. In *55th International Astronautical Congress*, 2004.

[7] L. T. Soto and L. Summerer. Power to survive the lunar night: An SPS Application? In *59th International Astronautical Congress*, 2008.

[8] P. Glaser. Power from the Sun: Its Future. *Science*, 162(3856), 1968.

[9] W. C. Brown, J. R. Mims, and N. I. Heenan. An experimental microwave-powered helicopter. *IEEE International Convention Record*, 13, 1966.

[10] W. C. Brown and E. E. Eves. Beamed Microwave Power Transmission and its Application to Space. *IEEE Transactions on Microwave Theory and Techniques*, 40(6), 1992.

[11] C. Cougnet, E. Sein, A. Celeste, and L. Summerer. Solar power satellites for space exploration and applications. In *55th International Astronautical Congress*, 2004.

[12] J. C. Mankins. Space Solar Power: The first international assessment of space solar power: opportunities, issues, and potential paths forward. *International Academy of Astronautics*, 2011.

[13] H. W. Brandhorst, J. A. Rodiek, M. S. Crumpler, and M. J. O'Neill. A solar electric propulsion mission for lunar power beaming. *Acta Astronautica*, 2009.

[14] V. Badescu. *Moon: Prospective Energy and Material Resources*. Springer, 2012.

[15] L. Johnson. Orbital space solar power option for a lunar village. In *10th IAA Symposium on the future of space exploration: towards space village and beyond*, 2017.

[16] S. Bowler. The new race to the Moon. *Astronomy & Geophysics*, 55, 2014.

[17] A. D. Torre, A. E. Finzi, G. Genta, F. Curti, L. Schirone, G. Capuano, A. Sacchetti, I. Vukman, F. Mailland, E. Monchieri, A. Guidi, R. Trucco, I. Musso, and C. Lombardi. AMALIA Mission Lunar Rover—The conceptual design of the Team ITALIA Rover, candidate for the Google Lunar X Prize Challenge. *Acta Astronautica*, 2010.

[18] H. Hemmati. *Deep Space Optical Communications*. Jet Propulsion Laboratories: Communications and Navigation Series, 2005.

[19] J. Walker. Flight system architecture for Sorato lunar rover. In *The International Symposium on Artificial Intelligence, Robotics and Automation in Space*, 2018.

[20] T. Nayfeh, B. Fast, D. Raible, D. Dinca, N. Tollis, and A. Jalics. High Intensity Laser Power Beaming Architecture for Space and Terrestrial Missions. *NASA Internal Report*, 2011.

[21] D. Raible and T. Nayfeh. Optical Frequency Optimization of a High Intensity Laser Power Beaming System Utilizing VMJ Photovoltaic Cells. *NASA internal report*, 2012.

[22] S. K. Reichmuth, H. Helmers, S. P. Philipps, M. Schachtner, G. Siefer, and A. W. Bett. On the temperature dependence of dual-junction laser power converters. *Progress in Photovoltaics: Research and Applications*, 2017.

[23] J. Schubert, E. Oliva, F. Dimroth, W. Guter, R. Loeckenhoff, and A. W. Bett. High-Voltage GaAs Photovoltaic Laser Power Converters. *IEEE Transactions on electronic devices*, 56(2), 2009.

[24] D. Goto, H. Hiroyuki, H. Suzuki, K. Kisara, and K. Ohashi. The Overview of JAXA Laser Energy Transmission research & development Activities and the Orbital Experiments Concept on ISS-JEM. In *Proc. International Conference on Space Optical Systems and Applications*, 2014.

[25] J. C. Mankins. SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array, 2012.

[26] Ryo Sugimoto, Kentaro Ichii, Ryuichiro Goto, Masahiro Kashiwagi, Tomoharu Kitabayashi, and Noriaki Shimada. 4 kW Continuous Wave Fiber Laser. *Fujikura Technical Review*, 2015.

[27] E. A. Shcherbakov, V. V. Fomin, A. A. Abramov, A. A. Ferin, D. V. Mochalov, and V. P. Gapontsev. Industrial grade 100 kW power CW fiber laser. In *Advanced Solid-State Lasers Congress*, 2013.

[28] STK Release Notes: Orbit propagators for satellites. http://help.agi.com/stk/. Accessed: 2018-08-10.