POWER TO SURVIVE THE LUNAR NIGHT: AN SPS APPLICATION?

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The Moon is regularly considered as a logic next step for human settlement in space, a first stage towards Mars exploration and test-bed for new technologies and concepts. The special lunar environment provides unique conditions for some research areas. The slow rotational velocity of the Moon entails long lunar days, with a synodic period of 29.5 days. This low rotation causes long shadowing phases on the lunar surface, up to almost 15 days for low and intermediate latitudes, which affect drastically the design of missions to the Moon's surface.

For low latitudes, the shadowing effects are even more remarkable: illumination conditions are favourable at lunar poles for the corresponding polar summers, achieving long periods of illumination. The most illuminated areas experience sunlight exceeding 80% of the lunar day. Illumination conditions for polar winters are the opposite, so that life-times of projected polar mission are normally restricted to last only a few months. Any extension of those missions needs a non-solar supply of energy to allow them survive the lunar nights. Nuclear power sources, reactors and radioisotope power sources (RPS) appear as the most promising candidates.

The possibility of using Solar Power Satellites (SPS) as a remote power source for lunar missions as an alternative to nuclear power sources has been studied and published. A lunar mission using SPS could be seen as a mission in its own right, but also as a technology demonstrator for solar power satellites. Depending on the mission design and profile, lunar surface missions might require regular or continuous power supply for surviving lunar nights. Depending on the orbital parameters, solar power satellites offer to provide either regular or continuous power for such missions.

Based on previous work by Cougnet et al., the present paper presents additional analysis of the different possibilities for options for SPS for lunar shadow coverage, with an emphasis on the orbital options. [1] It identifies the main issues and the consequences the particular dynamics related to the orbital requirements of any lunar SPS.

I. INTRODUCTION: THE MOON

The Earth's satellite is back to the centre of the attention of the main space agencies. Its accessibility and particularities identify it as the next natural step for human settlement, as a first step towards Mars exploration and a test-bed for new technologies and concepts. The unique lunar environment provides an exceptional spot for some research fields, both regarding the Earth - as space weather or albedo studies- or shielding its influence - as radio astronomy mapping from the far side of the Moon. Different missions are focused on the Earth's satellite, looking for answers about its origin, its composition, evolution and internal structure. As reflected in NASA's Vision for Space Exploration and ESA's MoonNEXT mission definition, one of the hottest topic for lunar scientific exploration is the study of the permanently shadowed regions near the lunar poles. Those craters are interesting sites for IR observations due to the low temperatures in continuous darkness. They are also good locations for in situ crust and mantle studies, but especially their singular conditions as possible volatile deposits make them the only known areas with reasonable possibilities of discovering ice on the Moon.

II. LUNAR ORBITS AND SOLAR POWER

The lunar orbit shows as particularity a tidal coupling to the Earth-Moon system: the synchronization between the Moon's rotation around its axis and its rotation about the Earth. This coupled rotation, caused by the gravitational attraction between the two bodies, results in a continuous facing of the same side of the Moon towards our planet. This slow rotation causes long lunar days on the Moon surface. The fixation between the Earth-pointing side of the Moon and the Earth caused by the tidal coupling allows a continuous communication between a lunar element and the Earth surface. Nevertheless, it also entails a lack of illumination of the surface of the Moon during the lunar night: the length of a lunar day is 29.5 Earth days. As a consequence, for low and intermediate latitudes the lunar night lasts one half of the synodic period, almost 15 days. In the regions near the poles, the shadowing phase may represent a higher percentage of the lunar day, depending on the Moon's season for the corresponding hemisphere.

These long shadowing phases shape radically the design of missions to the Moon; they limit the illumination time of the surface element, constraining the duration of the available periods for recovering energy from the Sun, but mainly forcing the probe to endure a long night and consequently limiting the mission performances, requiring at least a great amount of energy storage to survive the lunar nights. The illumination conditions of the most interesting lunar spots, located near the polar regions, allow polar missions to last several months. Any extension of their length into the polar winter likely either need a nuclear energy source.

III. THE SPS CONCEPT

Solar power satellites (SPS) consist roughly of a generally relatively large surface exposed to the sun, a solar to electric conversion system (e.g. photovoltaics, solar-thermal) and a wireless power transmission system, transmitting the converted solar energy either via laser or microwave-range radiofrequency to a remote receiver station, e.g. on planets or moons. Most other subsystems of an SPS are functionally comparable to those of any other spacecraft. The remote receiving station requires a receiving and conversion system (a rectenna for the RF system, or PV cells or a thermal generator for the laser systems) and possibly includes a power conditioning and at least short-term storage systems.

Studies on solar power satellites have been performed for over thirty years. Part of the involved technology has been proven, but its use for terrestrial applications is still questioned due mainly to the size of the orbital infrastructure necessary to allow their competitiveness within the energy market. At the moment, the expenses of an appropriate demonstration do not compensate the potential benefits of this new-concept renewable energy source.

IV. LUNAR SPS AS A POSSIBLE SOLUTION?

Depending on their operational requirements (lower temperature limits for components, operational power needs etc), lunar surface stations require efficient and possibly large energy storage capacity for surviving lunar nights. SPS may be considered as a possible power source and thus an alternative to nuclear power sources for such missions, including human missions.

A. Possible lunar scenarios

Planned and foreseen lunar missions are varied:

- Science missions. Both studying the Moon itself or its special characteristics towards the exploration of the cosmos.
- Future bases for human settlement.
- Test-bed towards Mars exploration.

The initial stages of the Moon exploration are based on robotic programs that will study the lunar environment at the same time they offer the possibility of demonstrating the key technologies that will be necessary for further developments. Lunar rover exploration plans range from small individual rover missions to complex mission involving orbital spacecraft, rover bases and swarms of rovers. Such missions might not need continuous coverage, but frequent illumination combined with some local energy storage. Next stages of Moon exploration activities would include components for human settlements and eventually lead to the construction an infrastructure required for a permanent base.

These successive phases for the Moon colonization imply different requirements to be fulfilled by the energy supply system. While regular but discontinuous illumination may be sufficient for robotic exploration, some unmanned missions and a permanently inhabited lunar base will require a continuous supply of energy. These diverse characteristics allow to consider an evolutive approach to the installation of SPS for the Moon, starting with a single lunar satellite to the establishment of constellations.

B. Power requirements of lunar surface missions

For the purpose of this paper, small lunar rovers require approximately 0.1-1 kW [1, 2], while medium-size permanent lunar bases need around 100 kW. [1] The technology choices of the SPS strongly influence the design of the receiving elements. Since the lifetime of SPS are generally much longer than small lunar missions and the efforts for its establishment prohibitively high with respect to single missions, technology choices for SPS need to be made in order to accomodate a whole range of planned lunar surface missions.

Wireless power transmission as considered for SPS have been demonstrated using radiofrequency systems (RF systems) and laser systems. The receiving system for the RF power is a rectenna, while laser systems use photovoltaic panels (in the visible and near infrared spectrum), or a thermal conversion system. Both systems have specific advantages and disadvantages as laid out in table I.

V. ANALYSIS OF POSSIBLE LUNAR ORBITS FOR SPS

An analysis of different orbital possibilities for SPS for a suitable lunar coverage has been done, identifying the main issues to be considered and the consequences the particular lunar environment introduces in the requirements for lunar SPS. One of the main questions to take into account when designing a lunar orbit for energy applications is the shadowing cone of the Moon. The SPS must be receiving direct energy from the Sun to be able to transform it and beam it down to the surface. Thus, the satellite must be outside of the cone of shadow of the Moon, at the same time that the shadowed surface spot is within its coverage area. This fact will affect the selection of the possible orbits for the SPS, in an attempt to minimize its eclipse period.

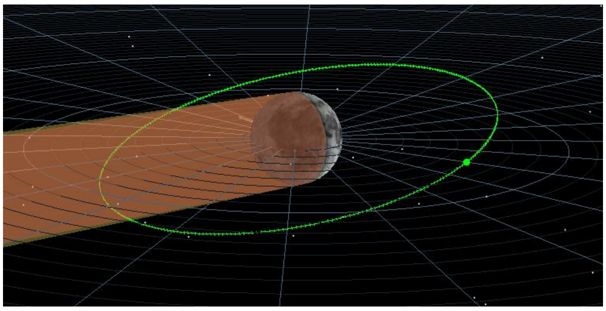

FIG. 1: Umbra cone in the proximities of the Moon

The proximity of the Earth and the Moon allows the consideration of the Earth-Moon Lagrange points as possible candidates for the location of SPS. Its positioning as lunar orbiter is also feasible, and the particular dynamics for lunar satellites open an interesting and challenging range of possibilities that is continuously being updated by different mission analysis research teams. [3–11] The two possible approaches have been considered in this paper.

A. Collinear equilibrium points of the Earth-Moon system, L1 and L2

The possibility of taking advantage of the three body equilibrium positions of the Earth-Moon system as a location of the SPS satellite offers an interesting opportunity to broaden the usefulness of the lunar SPS. The synchronization between the Moon's rotational period and the rotation of the Earth-Moon system has a direct effect on the visibility of the Moon surface from the Lagrange points: the SPS will always be on almost non-variable right ascension (α) and declination (δ) any visible Moon surface element for a satellite located in the Lagrange point. On the other hand, the SPS will not face the dark side of the Moon in a continuous way, but it will be the lunar surface spot what will be allocated easily and several times every lunar month. There is a small amount of the surface of the Moon, the polar ring between the far and the near side of the Moon, less than a 5% of the lunar surface, that cannot be covered by lagrange point satellites, which include some scientifically interesting regions near the poles. For the rest of locations, the L1 and L2 points present a very suitable possibility for the SPS to offer continuity and availability for surface coverage. The high distance between the Moon and the equilibrium points suggests the use of laser power transmission systems. The issues related to the existence of satellite eclipses due to the presence of the Moon can be minimized by the use of a Halo type orbit around the Lagrange point. A list of general assets and inconvenients has been considered for the Third Body system equilibrium points and for each of them in particular.

1. Lagrange points. General advantages

- The SPS will be located in an almost fixed position with respect to the surface probe: the pointing between the satellite and the Moon probe will be simple.
- The large distance between the Moon and the Lagrange points make the eclipses due to the Moon short for the satellite.
- Continuous coverage of the lunar probe for almost one half of the lunar surface, partial coverage for other locations.
- Easily usable for illuminating several independent rovers, only by pointing the SPS beam.

TABLE I: Comparison of laser and microwave power transmission options for lunar SPS

Laser Power Transmission	RF power transmission
+ same receiving system as for direct solar illumination	- dedicated rectennas
- SPS tracking receiving system	+ possibly light weight structure
+ higher focus allows for small receiving surfaces	- relatively large receiving surfaces required
- lower energy conversion efficiencies	+ high energy conversion efficiencies
- lower system maturity	+ mature systems
- difficult electronic beam steering	+ electronic beam steering, absence of moving parts
+ possibility of direct solar pumped lasers	- very large emitting and receiving structures (for large distances)
+ absence of atmosphere or safety concerns on Moon	

- Possible continuous coverage from the Earth.
- Possible utilization of the SPS as data relay, giving support for other lunar missions (only useful in the case of L2)

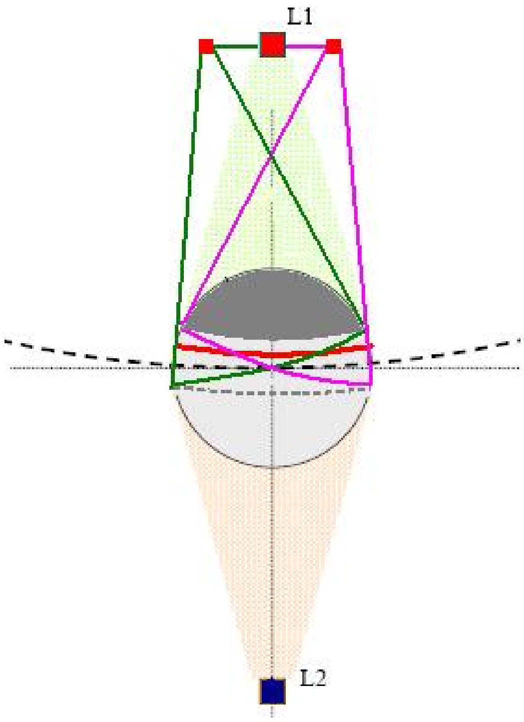

FIG. 2: Coverage of the lunar surface from the Lagrange points

2. Lagrange points. General disadvantages

- The high distance between the Moon and the Lagrange point causes higher energy losses and large structures for the emitting and receiving antennas.
- It needs separate launches for the SPS satellite and the rover.
- The SPS does not always face the dark side of the Moon: the surface element will face long periods, of one half of the lunar night of duration, without energy supply.

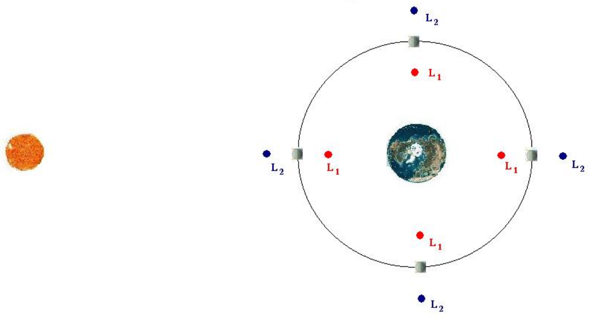

FIG. 3: Lagrange points and their relation with the lunar night

3. L1 advantages

- There's no need of acting as a communication support between the rover and the Earth: SPS orbit as close to the L1 point as possible: continuous coverage to ± 88 deg in latitude and longitude.
- The L1 point is the natural complement of the L2 point to provide with continuous coverage to almost any spot on the lunar surface.

4. L2 advantages

- The L2 lunar point allows to perform scientific missions from the far side of the Moon.

- It can act as an interface for the communication between rovers or lunar settlements located on the other side of the Moon. A Halo-type orbit will be required, and higher energy for the communication link through L2 due to its higher distance.

- It is an interesting location as placement for telescopes or other science missions, if using a strict L2 emplacement instead of a L2 halo. Thus, any radiation emission coming from the Earth would be shadowed by the presence of the Moon. As a disadvantage, it would not be possible to perform a continuous surveillance of the activity of the SPS; a lunar orbiter or a Halo orbiter in L2 would be required to perform the communication interface between the surface probe and the Earth and the SPS and the Earth.

- The insertion cost per satellite on L2 orbit is much lower than in lunar orbit. [12]

B. Lunar orbiter

The slow rotational velocity of the Moon about its axis, together with the small gravitational attraction exerted by the Moon and the presence of the Earth, entail the non-existence of Selene-synchronous orbits: their radius would be far larger than the sphere of influence of the Moon. Thus, the possibility of covering continuously a lunar area by means of a SPS with a period equal to the sidereal period of the Moon is not possible.

The orbital dynamics of a lunar satellite are very complex. The Moon gravity field is highly non-spherical, and the effect of the high order elements of its gravitational potential is significant. Very accurate models of the lunar gravity must be used. Recent lunar missions, such as Clementine and Lunar Prospector, are providing very good data that allow reproducing effects observed with actual spacecraft and not explainable so far, such as frozen orbits. [11]

The complex lunar gravitational field perturbs any satellite in orbit around it, causing drifts that often lead to an impact orbit. The improved knowledge of this complex non-spherical field shows the existence of families of orbits that maintain long-term stability. [1] Those discoveries enable the consideration of frozen orbits as candidates for low-maintenance cost lunar orbiters.

When studying higher altitude lunar orbits, the importance of the third body effects due to the proximity of the Earth effect the orbital dynamics of the lunar satellite. Accurate approximations of the Moon gravity field and the effect of the Earth in its apparent movement around the Moon are essential for a complete analysis of lunar orbits.

On the other hand, the umbra cone of the Moon, originated by the shadowing of the Moon, together with the Moon gravitational complexity, entails important consequences for the application of lunar satellites. For instance, no sun-synchronous lunar orbits exist for altitudes higher than 210 km, as orbits in higher altitudes are not eclipse-free at some part of the year. [7]

The time the satellite spends within this umbra cone is maximum when the Sun, the Moon and the satellite are aligned. Considering that the Moon orbit is inclined approximately 5 degrees with respect to ecliptic plane, orbits close to the equatorial ones will face every revolution a shadowing phase very adverse to the interests of the SPS. The distance needed for an equatorial satellite to avoid the cone of shadow of the Moon is the same order of magnitude as the distance between the Moon and the Earth. For the critical performance moments of the SPS, when the targeted lunar surface is at night time, this shadowing takes place in the vicinity of the orbital positions were the satellite should be emitting energy to the ground station. The way of avoiding this daily shadowing on the satellite due to the presence of the Moon is by means of an inclined lunar orbit or a high radius orbit.

Geometrically, this can be interpreted that: for every circular orbit of a given radius, a minimal inclination exists that would allow orbits to avoid to enter the umbra cone of the Moon.

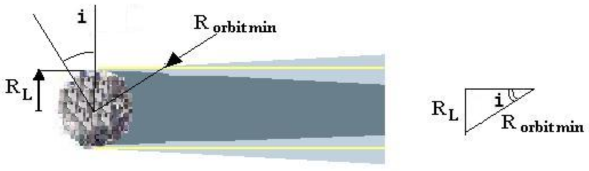

FIG. 4: Relation between the orbital radius and the orbital inclination

Though the minimum radius may be outside of the sphere of influence of the Moon, the symmetric is also valid, meaning that for every inclination we can find a radius that would avoid the umbra cone of the Moon. As an example of the orders of magnitude, the minimum radius to avoid the umbra cone of the orbit for an orbital inclination of 15 deg would be around 6800 km.

However, any kind of ideal lunar orbit (being this understood as an orbit that maintains constant the value of its orbital parameters) would present two annual periods of shadowing. This fact is related to the movement of the Moon around the Sun along the year, and the consequent turn in the axis of the

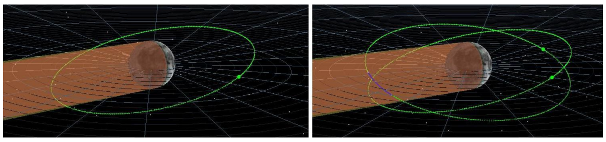

FIG. 5: Lunar orbits with i=15 deg, R= 6800 km. Left: RAAN selection avoids umbra cone. Right: a different RAAN introduces the satellite into the umbra cone.

umbra cone. Any ideal lunar orbit's orbital plane will be fixed in the inertial frame, and the turn of the orbital cone will intersect the orbit twice a year.

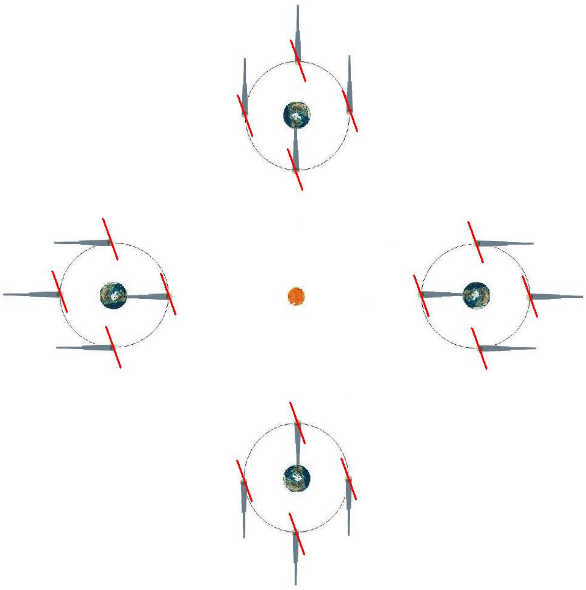

FIG. 6: Schematic view of the shadowing due to the turn of the umbra cone. In the top and bottom views, part of the orbit is shadowed by the Moon

This shadowing could be avoided if the RAAN of the orbit was controlled. Instead of maintaining an orbital plane fixed in the inertial frame, it could be forced to be fixed in the rotating Sun-Moon system. This would be achieved by forcing a RAAN drift equal to 2π radians per year, the rotational speed of the Moon around the Sun.

The need for station keeping against the perturbations present in lunar orbits, and the RAAN control that allows the orbit to be outside of the lunar cone in order to make the best of the SPS capability, translate into fuel requirements which might limit the life of the SPS mission. Simulations show that, due to the great perturbations exerted on them, low polar orbits may constitute an upper limit. The control of eccentric orbits that are not polar should be below this level, but will need special attention for every specific case: precise simulations of the orbit evolution will be required.

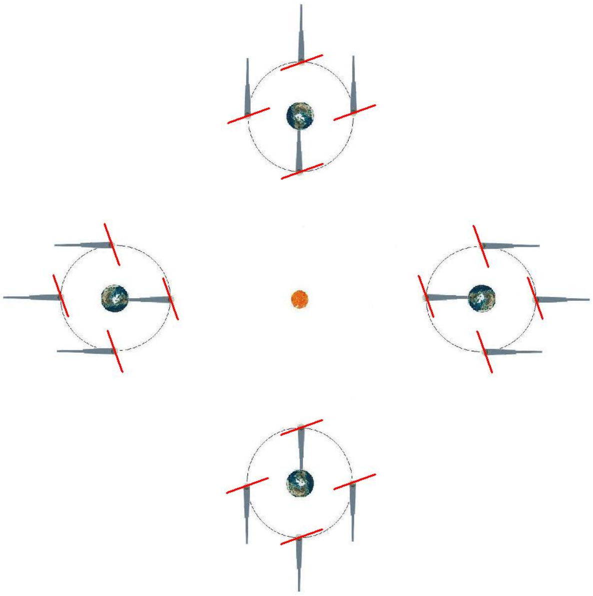

FIG. 7: Schematic view of the turn of the umbra cone. The orbit is illuminated the whole year

Several points can be highlighted as assets and inconvenients from the use of lunar orbiters as Solar Power Satellites. The different possibilities of using single orbiters and constellations are considered, and an overview of the most interesting orbits for the Moon is presented.

1. *General advantages*

- Capability of acting as lunar relay satellite due to its regular Earth visibility.
- Possibility of giving support to a wide range of possible rover missions to different parts of the Moon's surface.
- Possibility of performing scientific tasks: Moon surface survey, search for water (for high inclination orbiters)
- Almost continuous (several times per day) tracking of the far side of the Moon.
- Possibility of launching a small lunar probe and an SPS in a single launch, ready to perform a long duration mission; similar trajectories can be followed by the SPS lunar orbiter and the lunar lander down to a position close to the Moon, in the case of discontinuous coverage by a single orbiter. In the case of constellations, the launch of several orbiters can

be complemented by the release of other lunar rovers at different locations.

2. *Disadvantages*

- Frequent eclipses. Its frequency will depend on the Sun-Moon position, and the altitude and inclination of the orbit. High altitudes, high inclinations or high eccentricities may be needed in order to allow long visibility periods.
- Part of the orbit may simply be used for storing solar power on the SPS.
- Depending on location of the lunar probe(s), the communication with the Earth may coincide with the moments where the satellite is emitting energy for the rover.
- The inherent instability of the lunar orbit, together with the disproportionate perturbation due to solar radiation pressure on the satellite, will exert a determinant effect on the satellite, eventually forcing orbits towards an early impact agaist the Moon.
- After every satellite´s orbit around the Moon, the acquisition and tracking between the surface element and the SPS will be neered.

3. *Orbits around the Moon: types*

The large structures that constitute the SPS, involving massive components with high flexibility properties), intail that any manoeuvre of the SPS will imply high disturbances. The highly non-spherical lunar gravity field causes a large variability in the average eccentricities and orbital inclinations, leading to instabilities of lunar orbits, resulting in requirements related to orbital and attitude control. Thus, the maintenance of a satellite in a lunar orbit could require substantial fuel. Stable solutions are needed that will allow for minimal Isp requirements. For the search of stable solutions, both an accurate representation of the lunar gravity and the consideration of the Earth gravity field perturbation are required.

Different analysis based in the LP150Q model of the Moon gravity (based on Lunar Prospector measurements) are being performed by the Mission Analysis Department in ESOC, showing its better accuracy than the previous model GLGM-2 (based on Clementine measurements). [13] This new model is reproducing actual spacecraft behaviours already observed but not predicted so far, as it is the case of frozen orbits.

But the numerical analysis of the stability for Moon orbits needs special attention; an unexpected dependence on the initial conditions is observed in most of the orbital analysis, showing different stability characters by a slight change in the orbital parameters. Thus, the prediction of the stability regions will depend extremely on the selection of the study conditions; a enormous number of simulations of orbits with very similar orbital parameters has to be analysed to be able to extract the information of the different stability characters of a region. [8] Low altitude families of stable and near-stable repeat ground track solutions have been found for near-polar inclinations. [1] Other stability regions for periodic solutions have been found, as the h1 and h2 families in the synodic frame. [6, 10] Taking into account other sources of perturbation, as considering the four body problem for the analysis of the lunar orbits, changes significantly the size of the regions of stability.

Some of these solutions, decribed in the next paragraphs, have interesting characteristics for SPS applications. They are the Repeat Ground Track Orbits, the Frozen Orbits and the RAAN controlled orbits. Several research groups are performing work on the two first type of lunar orbits, and their results have been used in this work. The RAAN controlled orbits have been identified as an interesting solution during the lunar SPS analysis. They are a topic that has not been studied so far; further work will be needed to determine its feasibility.

a. Repeat ground track orbits Very interesting potential orbits for Solar Power Satellites could be the repeated ground track (RGT) orbits. RGT orbits are a kind of periodic orbits that perform a number of revolutions around the body while the attractive body performs one single revolution, so that their track is a closed line on the body's surface. In the case of the Moon, they present a periodic movement in the selenocentric system, thus being periodic in the six rotating Cartesian coordinates by definition.

Instead of performing the illumination of a surface probe every satellite revolution, by placing it into a controlled orbit that always covers the same lunar area (implying enormous fuel expenses to maintain the satellite linked with the selenocentric system), the area can be illuminated every few satellite revolutions, by means of placing the SPS in an RGT orbit.

The main parameter that defines the RGT orbit families is the integer ratio of spacecraft revolutions to body revolutions during a full period. This ratio, for the RGTsolutions found so far, is between 70 and 300, meaning that a satellite in a RTG has to perform between 70 revolutions (high altitude) and 300 revolutions (low altitude) to illuminate the same lunar area. [1] The difference in the number of revolutions to be performed by the satellite is mainly related to the semimajor axis of its orbit, having a direct impact in its period. In any case, for the RTG orbits found so far, several days will pass between two consequent illuminations of the same lunar area, decreasing the performance of the surface element; on the other hand, many different areas can be covered and the fuel expenses are reduced drastically.

Based on a numerical analysis considering the gravity potential and the Earth attraction, the results of the study of RTG orbits that present long-term stability for the case of the Moon so far have shown the need for low-altitude near-circular orbits, obtaining good stability results for near polar orbits. The stability of the orbits decreases by the use of high altitude orbits, and the model to study them must consider also several other sources of perturbation, as higher order coefficients for the Earth gravity and the Sun attraction.

Research is still to be done for lunar orbits analysis. There may still be unknown solutions for near-stable RTG orbits. They may allow for a long-life possibility for the SPS.

Several drawbacks are linked to the use of RGT orbits

- RGT orbits don't provide continuous coverage.
- RGT orbits are low altitude orbits. The lower the orbit, the higher their stability due to less perturbations from other factors than the lunar gravitational field, but:
  - The lower the orbit, the shorter the in-sight time, which can be another problem for the acquisition and tracking of the rover.
  - The lower the orbit, the longer the eclipses due to the Moon presence between the Sun and the SPS satellite. The RGT orbit doesn't guarantee the illumination of the satellite by the Sun when it is over the surface probe.
- The RGT orbits are based on approximations to the lunar gravity field. Actual orbits have perturbations, and Station Keeping will be required to maintain their parameters. The RGT orbits found so far are high inclination, as all the families are around 90-91 deg. Thus, the station keeping manoeuvres they need is, in principle, higher than the required if they were low inclination orbits, though the complexity of the lunar field entails specific simulation for each case.

The low altitude of the actual RTG orbits may entail an incompatibility with the need of illumination of the SPS in the required times. Specific studies related to particular lunar areas must be accomplished.

b. Frozen orbits The term "frozen orbit" is typically used for an Earth orbit in a low altitude that, due to the non-spherical gravity field of the Earth, maintains its eccentricity and argument of periapsis. Thus, the satellite shows an orbital regularity, as it will always pass at the same altitude for a given latitude. A more general definition of a frozen orbit could be considered, where any of the orbital parameters may be held constant.

The utilisation of frozen orbits reduces the need of actuation, improving the performances and increasing the life of the satellite. This characteristic makes frozen orbits interesting candidates for low-maintenance cost lunar orbiters.

The study of frozen orbits in low altitudes for the Earth can be done in a simple way by the consideration of the J2 and J3 terms of the Earth gravity potential. The higher complexity of the lunar satellite dynamics shows that a more sophisticated approach is needed, and different results for frozen orbits are obtained when different approximations are considered. The most promising studies for lunar frozen orbits so far are:

- Ely and Lieb have found highly elliptical frozen orbits (e 0.6) at high inclinations by considering the gravitational field of the Moon and the Earth and Sun perturbation. [5]

- Ramanan and Adimurthy, and Park and Junkins have analysed near circular frozen orbits, through a lunar zonal potential up to degree 9. [14, 15]

- Elipe and Lara have studied the variational equations, and found critical semi-major axis, eccentricity and inclination, through a zonal potential limited to degree 7. [16]

- Folta and Quinn have studied Low Lunar Orbits (<750 km) with the consideration of a full potential body plus 3rd body effects, and elliptical orbits by analysing the Lagrange planetary equations, and performing a subsequent modelling. [11]

The complexity of the study indicates that new frozen orbits may be found by changing the way of facing the orbital problem and by spanning the possible orbital parameter combinations. The following chapters are based on the most promising results from Folta and Quinn, and Ely and Lieb for lunar frozen orbits, showing their characteristics and possible applications. [4, 5, 11]

Low lunar orbits An analytical study of the lunar problem, verified with a full potential model with third body effects, was performed by Folta and Quinn. [11] The orbital motion for low lunar orbits, with altitudes lower than 2200 km., cannot be predicted by analytical expressions; it is required to model the gravitational accelerations in numerical analysis.

The numerical analysis of a full potential model for the Moon shows the existence of near circular close to frozen orbits for inclinations higher than a minimum one, close to 30 deg. Several frozen orbits have been found for low lunar orbits. All of them have very small eccentricities and very low altitudes, presenting apoapsis below 500 km in all cases. The argument of the perigee of those orbits presents a libration around its frozen value, maintaining its location for one year simulations without the need of any control.

Low circular frozen lunar orbits may represent a very good solution for the illumination of the lunar poles. Despite their good characteristics as frozen orbits, the interest of avoiding the umbra cone of the Moon limits the possibility of using them as SPS orbits for probes located in areas close to the polar regions. For other surface probe locations higher altitudes would be needed.

The semi-major axis will also affect the period of the orbit, limiting the time of the contact between the satellite and the surface. Specific analysis have to be made to determine the capability of energy transmission for the SPS under those conditions.

High eccentricity orbits The motion of higher altitude lunar orbits ($>$ 500 km) is dominated by the third body perturbations due to the presence of the Earth. The analysis of the effects of the central attraction from the Moon and the Earth on the lunar satellite shows interesting results for orbits with high eccentricity.

Based on the analysis of a reformulation of the Lagrange equations, Ely discovered that for inclinations above 39 deg and initial arguments of the periapse of 90 or 270 deg, it exists a value of the eccentricity that maintains the eccentricity and the arguments of the periapse around their nominal values. Thus, it is possible to find an eccentricity for which the argument of the periapse oscillates between two close values. [4] Trajectories with inclinations smaller than 39 degrees, the argument of the periapse would circulate, and the frozen condition would not be fulfilled as the periapse of the orbit would turn.

Ely and Lieb have demonstrated that those high eccentricity orbits can be used for the design of a constellation of long-life frozen orbits that provide a continuous coverage of a polar lunar region. [4, 5] Three satellites would be necessary, allowing the redundancy of the link between the SPS and the surface element by the continuous view of two satellites from the polar area. Global coverage can be achieved by means of six satellites, using the same kind of orbits and separating the two orbital planes in 90 deg in the RAAN, and apoapsis in opposite orientations.

c. Controlled RAAN orbits An important step to be addressed in future studies of the lunar gravitational field would be the use of frozen orbits with controlled RAAN introduced in the Lunar orbiter section introduction.

These orbits would have a RAAN drift of 2π radians per year, making the orbital plane turn at the same speed the Moon turns around the Moon, thus obtaining a fixed plane in the Sun-Moon system.

The possibility of avoiding the umbra cone of the Moon by means of a rotation of the orbital plane would allow to illuminate a part of the shadowed area of the Moon by a single satellite every revolution in its operational life; thus, a lunar probe would only need to be equipped with enough energy storage to survive the part of the orbit the SPS is not illuminating it. Thus, an “almost continuous coverage” for the night surface area would be provided by one single satellite.

Continuous illumination would be obtained by the use of three SPS in the same controlled RAAN orbit. Global coverage would be achieved by two satellites in two different planes. Global continuous coverage would need the use of six controlled RAAN SPS in two different planes.

4. Number of satellites

Single orbiter A single orbiter providing energy to a small probe could be launched in a single launch with the surface element. It would offer an interesting solution as a power supply for one to several rovers in different positions. The control of the orbital parameters to correct the effects of lunar perturbation, together with the control of the RAAN angle of the orbit to correct the seasonal apparent movement of the umbra cone, would allow transmitting power from the SPS at every revolution, providing with discontinuous coverage for a designed lunar area.

The use of a frozen low lunar circular orbit would provide with discontinuous coverage for the polar regions.

Constellation A constellation could provide full coverage for a single rover or a single manned mission (several satellites in a single or multiple orbits). The number of satellites depends on the location of the surface elements. Due to the complex characteristics of the Moon orbiters, the design of constellations is highly dependant on the orbits selected for the satellites forming them. In the case of a manned mission, redundancy of the elements must be considered to increase the safety of the mission.

Considering the adequate selection of orbit parameters, an overview of the coverage provided by the different possibilities is as follows:

Two orbiters Two orbiters performing in different orbits performing RAAN control would cover the whole shadowed surface of the Moon, transmitting power every SPS revolution, providing with discontinuous coverage of the whole lunar night.

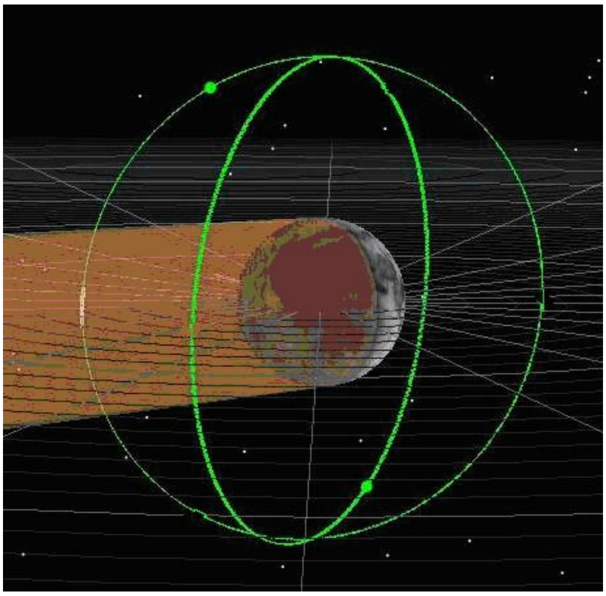

FIG. 8: Example of a possibility of the use of two satellites in circular orbits to provide with discontinuous coverage for the whole lunar night

- Three satellites with the same orbital parameters and separation in perigee argument, performing RAAN control, would provide with continuous coverage for a designed lunar area.

- Three satellites, same high eccentricity orbit: continuous coverage of the whole lunar night for specific areas close to the poles, providing the redundancy required for manned missions.

- Six satellites located in two different orbits, would provide with continuous global coverage for the whole lunar night.

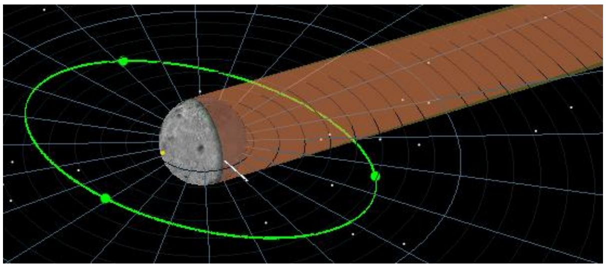

FIG. 9: Example of a possibility of the use of three satellites in the same circular orbit to provide with continuous coverage for the whole lunar night

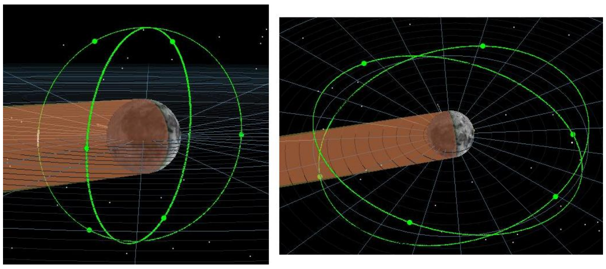

FIG. 10: Example of two possible constellations providing with continuous global coverage

C. Orbit selection

The selection of the SPS orbit requires multi-objective optimisation, including minimizing the fuel consumption, accessibility from a multitude of ground locations, overall thermal and energy storage needs. Concerning the minimisation of fuel consumption, the use of frozen orbits is advisable. For continuous coverage, RAAN controlled orbits would be the best option. If the surface probe is on the far side of the Moon, a convenient option could be the utilisation of the L2 Lagrangian Point: the insertion of a satellite in L2 is one order of magnitude cheaper in terms of Δ V than the insertion in a frozen lunar orbit, and the change of lunar spot to be illuminated on that side of the Moon would only require the repointing of the SPS. [12] A satellite in the Lagrange point would not guarantee continuous coverage. The final selection of the SPS orbit and the number of satellites to perform the task will be determined by the position of the surface element and its necessity of continuous supply of energy. The estimations of the ΔV required in each of the options presented in this work will show the actual feasibility of the solutions proposed The new results of the analysis of the lunar gravitational field must be considered to incorporate them as potential solutions for the lunar night problem.

VI. CONCLUSIONS

Energy supplied by solar power satellites for lunar surface missions may expand their lifetime by providing enough energy to survive the lunar nights, otherwise currently possible only with the use of nuclear power sources. Such an application of solar power satellites would allow to combine the direct benefit for lunar exploration with the indirect benefit of providing a full system level technology demonstration of solar power satellites for its potential future use to generate electricity for terrestrial applications.

This paper presents an analysis of the orbital options for solar power satellites to power lunar surface missions.

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