PRE-PHASE A SYSTEM STUDY OF A COMMERCIAL-SCALE SPACE-BASED SOLAR POWER (SBSP) SYSTEM FOR TERRESTRIAL NEEDS

TN3 – ARCHITECTURE SELECTION REPORT - SPACE SEGMENT DESIGN – ANNEX 1

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

July 17th 2023 – Revision 1

ESA Contract No. 4000141171/23/NL/MGu.

SBSP Architecture Selection Report

Appendix 1: Space Segment Architecture

[TN3]

SBSP Pre Phase A Study

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Change Records

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
Issue 1	04/07/2023	1st issue for ASR	Team
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1 Introduction

1.1 Scope and purpose

This document presents the TAS activities of WP 330 consisting in a support to the architecture trade-space definition for Space segment.

1.2 Applicable documents

ID	Title	Reference	Issue
[AD1]	ADL Contrat	400011411721/22/NL/MGu/TAS	1

1.3 Reference documents

ID	Title	Reference	Issue
	Retour stakeholders		

2 Overall orbital architecture

Before describing the spacecraft, it is necessary to consider the overall space segment architecture by describing the necessary reflectors to be placed in orbit to comply with the expected irradiance and total solar power to be provided to the ground segment.

In order to explore the trade space of the possible constellation architectures, dedicated spreadsheets were elaborated for both strategies, allowing to quickly assess the number of Direct Solar Reflectors (DSR) or Solar Pumped Laser (SPL) units needed to feed the ground power plants and a rough estimation of the number of launches to set space segment in orbit and maintain it. Its main inputs are the size of reflectors, the orbit altitude, and the solar power density provided on the ground. It also evaluates the number of power plants to be installed on Earth. This user friendly tool was also delivered in the DM4-Trade Space Model to understand and manipulate the sizing levers of the overall SBSP system.

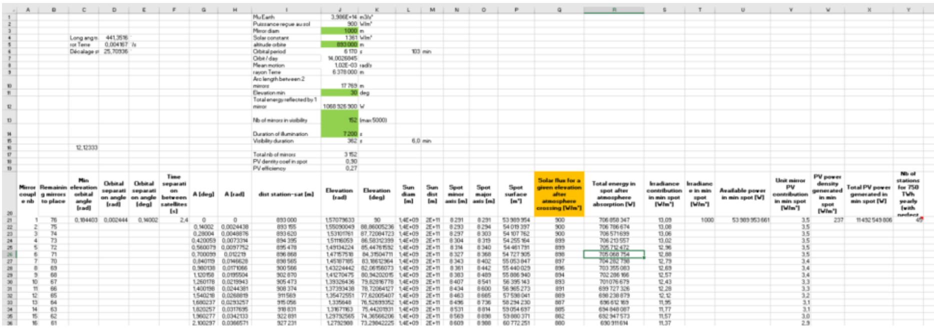


Figure 1 -Excel SBSP constellation sizing tool

In addition to these preliminary computations, several simulation runs with simu-CIC and OSIRIS tools were performed for the most interesting identified cases to confirm they were viable from detailed orbital point of view, considering eclipses, seasonal effects, …

In this preliminary trade space exploration we first faced the geometrical fact that the spot size of the beam on Earth is proportional to the Sun apparent angle and to the distance between reflector and ground power plant. The higher the reflector is, the larger is the spot size. The use of a converging mirror instead of a flat mirror can only improve the spot size by the diameter of the mirror. This is only interesting when the spot size is of the same order as the mirror dimension. For example, a large LEO flat reflectors of 1 km diameter at 800 km of altitude has a spot size is 8.43 km diameter while a focused mirror allow to get a 7.43 km spot size. But this gain decreases with altitude, as shown in the table below.

Solar constant	W/m2	1361	1361	1361	1361	1361
Sun diameter	m	1,39E+09	1,39E+09	1,39E+09	1,39E+09	1,39E+09
Sun Distance	m	1,50E+11	1,50E+11	1,50E+11	1,50E+11	1,50E+11
Sun aspect angle	rad	0,01	0,01	0,01	0,01	0,01
Orbit altitude	**m**	**36 000 000**	**4 000 000**	**1 400 000**	**800 000**	**600 000**
Mirror diameter	m	1 000,00	1 000,00	1 000,00	1 000,00	1 000,00
Number of mirrors		1,00	1,00	1,00	1,00	1,00
Spot diameter with flat mirror	km	335,24	38,14	14,00	8,43	6,57
Spot diameter with parabolic mirror	km	334,24	37,14	13,00	7,43	5,57
Total power reflected on Earth	MW	1 068,93	1 068,93	1 068,93	1 068,93	1 068,93
Irradiance in spot on Earth with flat mirror	W/m2	0,01	0,94	6,95	19,16	31,52
Irradiance in spot on Earth with parabolic mirror	W/m2	0,01	0,99	8,06	24,67	43,86
Irradiance gain between parabolic and flat mirror	**%**	**1**	**5**	**14**	**22**	**28**

Figure 2 – Impact of the orbit on the spot size on Earth

At GEO orbit, the spot size is so large that the gain of using a converging mirror is negligible (1%).

These principles are detailed in the Thales Alenia Space technical note dedicated to optical considerations.

Because the spot size increases with altitude, the reflected flux for a given reflector surface is diluted in a larger ground surface, and the irradiance decreases, implying the use of more reflectors to compensate that.

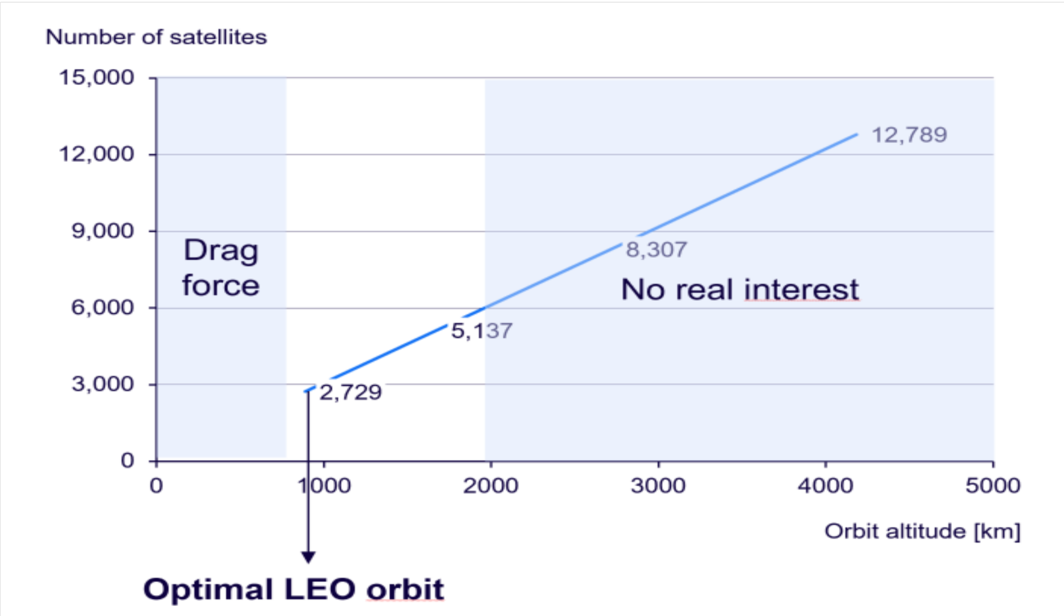


Figure 3 - Number of 1 km diameter reflectors needed to compensate the altitude increase and irradiance in spot decrease (points for SS0 orbits)

These facts led to discard Direct Solar Reflection solutions for orbits higher than LEO (> 2 000 km): because it implies too large and numerous reflectors well beyond what is reasonable.

Then now among the LEO orbits the most interesting are:

1. those whose 12 hours is a multiple of their orbital period

2. those that are in Sun Synchronous Orbit

The first condition allows to flyby the same ground location twice a day, which allow for a same set of scrolling reflectors to provide solar power twice a day as long as the reflector is not in eclipse and the ground station is not in daylight.

The second condition allows synchronizing the orbital plane rotation with the Sun direction. As a result, the reflectors will always flyby the ground sites at the same solar time, which can be initially chosen. In our case, the most interesting local solar time is 6h – 18h, meaning that the reflectors will fly by the same region at sunset and sunrise. This is very interesting in our mission to extend the sunlight duration. Moreover, LEO SSO are necessarily almost polar orbit, which allows to flyby every places on Earth, even high latitudes. These SSO are represented by the blue spots on the graph above.

The best is to cumulate both conditions. This is why for the next part of this note we will consider LEO SSO (6-18) for Direct Solar Reflection.

In addition to these preliminary computations, several simulations with SIMU-CIC tool were performed for the most interesting identified cases to confirm they were viable from detailed orbital point of view: eclipses, seasonal effects, station visibility…

The simulations support the preliminary computations to precisely determine the orbital parameters. Especially, on a given orbit, the true Argument Of Latitude (aol) has to be defined to fly over the station at zenith.

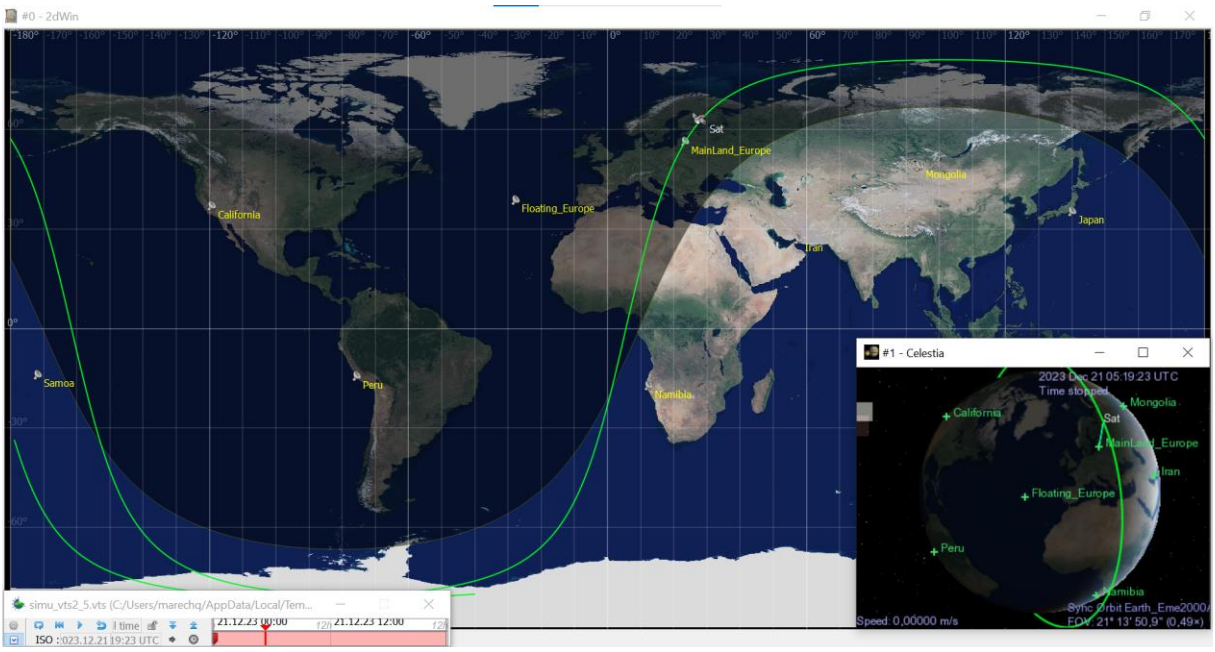


Figure 4 - Phasing of the SSO repeat groundtrack (14/1) at 888.32 km of altitude to fly over the station Main Land Europe, with Earth view.

It is also important to consider the ground stations visibility with a 30° elevation angle to size the constellation.

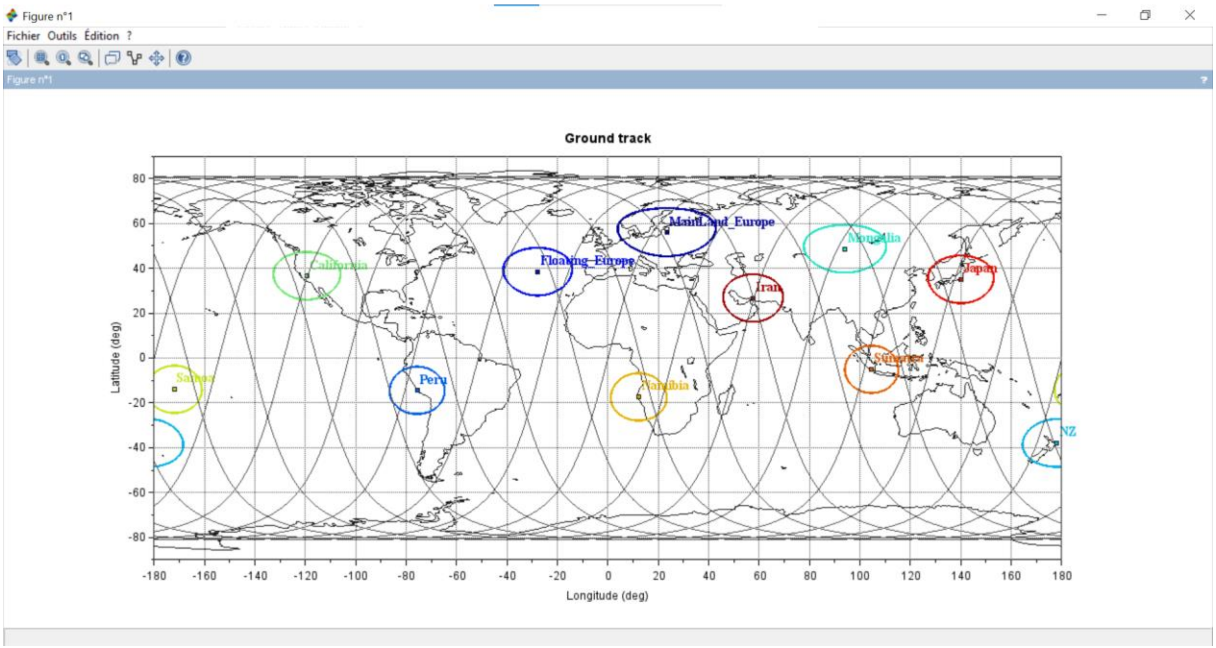


Figure 5 - 24h ground track of the SSO repeat groundtrack (14/1) at 888.32 km of altitude with station visibility (30° elevation angle)

The tool SIMU-CIC also allows to visualize small clusters of mirrors and the projected area of illumination on ground.

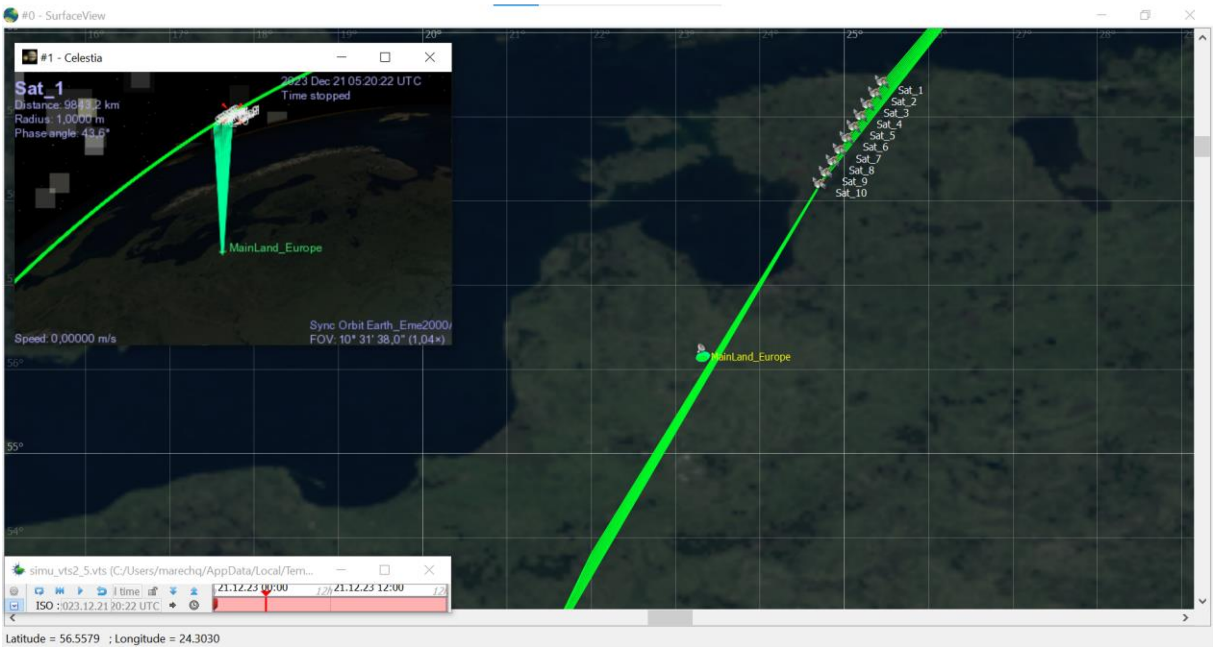


Figure 6 - phasing of a mirrors cluster on the SSO repeat groundtrack (14/1) at 888.32 km of altitude (over the station Main Land Europe).

2.1 Direct Solar Reflection in LEO

First of all, we considered orbits above 800 km, as below this altitude the drag force would be prohibitive on the large and lightweight platforms, and therefore implying a huge amount of fuel (see details in part 3).

Many cases were run but we will discuss here one of the most interesting ones which will also be a good candidate for comparison with Solar Pumped Laser solutions.

The case we will focus on is a constellation of 3 152 reflectors of 1 000 m of diameter each, placed on an SSO at 890 km of altitude.

SSO at 890 km is convenient for allowing to always have the same local solar time and because 12 hours is a multiple of its orbital period. This makes it possible to extend illumination time of any of the PV farms after sunset and before sunrise each day and therefore making the constellation more profitable (we will see below that unfortunately it was not possible).

This constellation setup allows to have “permanently” 152 scrolling reflectors in visibility of a single ground station with an elevation above 30 deg. Below this elevation the amount of air along the line of sight absorbs too much power. These 152 visible mirrors are all directing their beam towards the same ground station. Clearly, since reflectors are not seen from the ground with the same elevation, each conical beam creates an elliptical spot on the ground. However, in the end this is the superposition of these ellipses which will allow to reach the expected irradiance of 1 000 W/m² in a circular spot of 8.2 km of diameter to feed the PV farm. It means that ideally the PV farm would occupy this entire spot surface.

1 000 W/m² was estimated by Engie to be the good compromise for the PV farm to work efficiently. Below 200 W/m² the PV farm would not be able to produce electricity.

However, the goal of achieving an instantaneous production of 1 000 W/m², is not enough. The final objective is in fact to size the system to produce 750 TWh per year with the SBSP system. We then need to multiply the number of reflectors in orbit and PV farms on Eath.

Consequently, the “train” of reflectors was extended to 3 152 units in order to provide during 2 hours a continuous irradiance of 1 000 W/m² on a given PV farm. Moreover, the number of PV farms was extended to 89 stations (of 8.2 km of diameter each). In these conditions, the SBSP could produce yearly 750 TWh.

Remarks:

- If we look into details the orbital train, each reflector’s orbital plane is in fact shifted by a small right ascension of the ascending node angle with respect to its predecessor in order to make all reflectors flyby the PV farm vertically and doing so ensure the maximum irradiance.

- The PV farms cannot be located adjacently, because it takes time for each reflector to redirect the beam towards the next ground PV farm. This duration is difficult to assess at this time of the project so a reasonable distance along track of 4 000 km was considered for instance. This point will be analysed further in the study.

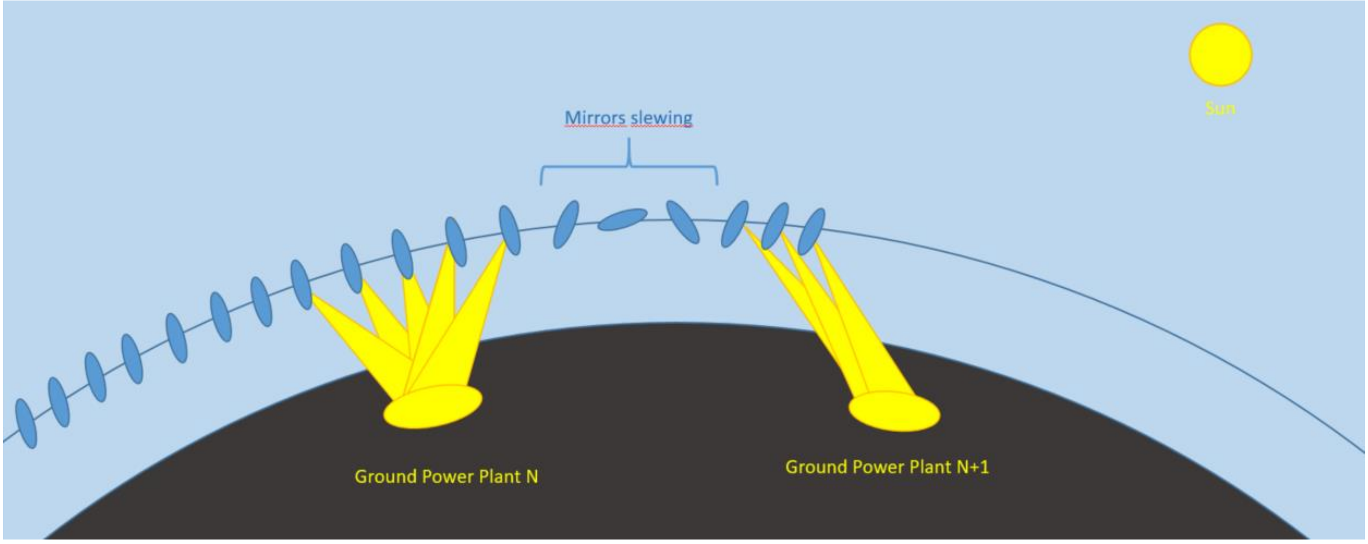


Figure 7 -Scrolling relfectors train, illuminating PV farms successively

The reflectors train length providing 2 hours continuous irradiance was sized thanks to simulations. It was not possible to extend it further because beyond that duration the reflectors would be in eclipse.

Simulations also showed that unfortunately, due to seasonal effects affecting high latitude PV farms, it was not possible to use the same “reflectors train” to feed PV farms twice a day, making it more efficient. This implied to size the number of reflectors and PV farms for a single flyby per day. However, considering only PV farm in tropical zones could make visibility twice a day all over the year.

Finally to produce 750 TWh, the overall ground footprint generated by all the 89 PV farms is of 480 000 hectares, equivalent of a single spot diameter of only 39 km.

Given the optical geometry limitations of DSR system, mainly the fact that due to Sun apparent angle applied on long distances between reflector and the PV farm, the DSR constellation requires increasingly larger overall surfaces while altitude rises. This supposes more and/or larger reflectors.

Moreover, as explained in the optical technical note, the focalisation of the reflector or the use of other optical systems cannot really improve this. This consequently limits the DSR to lower orbits in order for it to remain reasonable systems. The counterpart is that is implies scrolling trains of reflectors and necessitate many ground stations seen successively.

Please note that the document details the rationale of the orbit and several SSO orbits have been studies and different cases presented in annex to support the trade-off. Two major issues avoid to illuminate 24/7:

- "The reflectors train length providing 2 hours continuous irradiance was sized thanks to simulations. It was not possible to extend it further because beyond that duration the reflectors would be in eclipse."

- Deploying a reflectors' train to illuminate 24/7 would generate a huge volume of SPS (roughly x6 than the DSR architecture proposed) with potentially no so much added value (illuminating PV during the day creates no added value) or public acceptance (illuminating a large spot size with light pollution)

2.2 Solar Pumped Laser in GEO

The limitation of optical geometry in the capability to concentrate the solar flux in the spot on Earth led us to consider more innovative solutions based on light beam amplification: optical lasers.

Indeed bibliography and discussions with laser experts exposed that it is conceivable to generate a laser beam directly from concentrated Sun light. This is called Solar Pumped Laser.

Then the other strategy considered in this study is a constellation of Solar Pumped Laser (SPL) units in GEO. Its technical description is given in part 3 while in this section we will describe what could be the sizing of such a constellation.

First it is important to highlight that the laser beam technology we considered is the same as those under development in several laboratories and works at 1064 nm. We used quite conservative figures in our approach (efficiency, beam divergence angle, …) so that it is likely that further analyses prove this system even more capable.

As for DSR, we considered 1 000 m diameter reflectors, collecting the Sun light and redirecting it towards the SPL components.

The main advantage of having a very narrow divergence angle is to be able to place the SPL units in GEO and then to have a permanent (24/7) view on the ground power plant. The main counterpart here is that the beam is very concentrated but in a very small spot. As opposed to DSR where beams had to be cumulated on a spot, here each SPL can generate small spots (hundreds of meters) with thousands of W/m² of irradiance. We then tried to size up the system in order to find the right irradiance between irradiance and spot size and number of units.

The solution is a constellation of 2 889 SPL units in GEO. Each generating on Earth spots of 163 m of diameter. We made the reasonable hypothesis to use on PV farms photovoltaic panels specifically designed to work with laser beam wavelength and intensity providing an efficiency of conversion of 60% and able to deal with an irradiance of up to 2 400 W/m².

Doing so we obtained a year electrical production of 750 TWh, with a footprint of 6 000 hectares of PV farm, equivalent of a single spot diameter of only 9 km.

Remarks:

- It is important to highlight that in SPL PV panels are permanently and optimally pointing reflectors direction. While in DSR since at any time each visible reflector is seen with a different elevation angle, the PV panels have to remain horizontal, reducing their overall efficiency. The counterpart is that specific PV panel for SPL are not suited to work with the full Sun light spectrum. However, this is a minor point since they collect laser beam 24h a day.

- Even if the spots are small, they can be adjacent to each other because each one is generated by a single steady SPL unit, minimizing the PV farm footprint.

- Other solutions than specific PV panel could be advantageously considered to exploit the SPL more efficiently, i.e. to a higher level of concentration which is easily feasible using a larger concentrating telescope avec the laser pumping. For example, solar thermal farms could deal with higher irradiances reaching a conversion efficiency of up to 50% but on a much higher irradiance. This solution is under assessment.

- GEO orbit is already pretty busy and available slots are not frequent, so adding 2 889 more satellites is a challenge. However, it is possible to operate several reflectors in a single slot this is called “co-location”. But assuming that we can manage to fill slots with up to 29 co-located reflectors, it still requires to find 100 free slots to do so.

2.3 Trade-off results

Comparing LEO DSR and GEO SPL considering their relative advantages and shortcomings we were able to elaborate the comparison table below for a same unitary mirror size of 1000 m.

In red are the most significant shortcomings or difficulties to be overcome and potential showstoppers. Green is the match winner, orange the looser.

	LEO DSR	GEO SPL
Number of platforms in space	3152	2889
System complexity	"simple" large focusing reflectors	Large focusing reflectors + collector + laser pumping + télescope
	Complex slew capability	Steady pointing
Launches	3153 A6 or 765 Starship (resp. 60 and 15 years with 1 launch/week)	10300 A6 or 3600 Starship+spacetruck (resp. 200 and 70 years with 1 launch/week)
Min number of ground power units	89 stations geographically separated	Very flexible: 1 big to 2889 small
Availability	+2h/day	24/7
Ground foorprint	480 000 ha	6 000 ha
Environmental effects	Large elliptical spots wasting power outside of the core spot	Small circular beams
	Visible trails of hundreds of satellites (in LEO) 2h after sunset	Very small if not invisible
	Visible reflected beam	Beam invisible (NIR)
Yearly station keeping fuel cost per unit	540 kg	80 kg
Potential techno/performance increase	Limited	Promising
Reuse existing PV farms	yes	yes

Figure 8 -Trade-off results synthesis

(Please note that at first stage, evaluation considers only SBSP surface and Celestlab atmospheric density model. But with very conservative parameters (ISP 1660s, DV 600 m/s per year, drag force 0,28N, reflectors perpendicular to velocity). For next step, station keeping will be updated considering all perturbances.)

Looking at this synthesis, GEO Solar Pumped Laser seems to be the most appealing. Its two main shortcomings are the launch solutions which are far from compliant with the overall mass to place in GEO, (but this is also true for LEO DSR) and the technical complexity which is possibly over estimated due to the lack of analysis in making solar pumped lasers in space as far as we have seen in the bibliography.

Another advantage of the SPL is its potential performance increase. Indeed, we used quite conservative values corresponding to today laboratory results. For example, for the space segment, experts do believe that in a decade 10% of efficiency could be reached in solar pumping laser, while we considered 5%. In the same way, we considered modified PV farms on the ground with limited irradiance while other technologies like thermal solar panels could be more efficient at higher irradiance.

In addition, the results of a specific trade-off for the exploration of the different orbit altitudes for different mirror size is in annexe.

2.4 Launch considerations

The SBSP system will be considered as operational when it reaches a yearly production of 750 (REQ-SBSP-SYS-091). As seen in the previous section it implies a very large number of reflectors for both strategies: LEO DSR or GEO SPL.

For LEO DSR, it was assessed that a single platform mass should be of about 17 t. Assuming Ariane 6 EVO and a new generation of European heavy fully reusable launcher injection mass in LEO SSO of respectively 17 t and 70 t, it leads to respectively 3 153 and 765 launches.

For GEO SPL, it was assessed that a single platform mass should be of about 25 t. Assuming Ariane 6 EVO and a new generation of European heavy fully reusable launcher injection mass in GEO of respectively 7 t and 20 t with a space truck support, it leads to respectively 103 000 and 3 600 launches.

Given the high number and pace of launches to reach an operational SBSP, fully reusable launchers are key because they promise a high frequency of launch, with minimum maintenance activities and minimizing resources consumptions and environmental impacts. Moreover in some cases, upper stages with cargo capability could return used or faulty elements for recycling on Earth.

Consequently, in the frame of this study, we considered the capabilities of a post Ariane 6 heavy reusable launcher, with performances close to those of SpaceX's Starship ones.

The counterpart of heavy fully reusable launchers concepts is their limitation to LEO. It implies to complete them to rely on a space logistics ecosystem composed of space trucks, fuel depots, on-orbit servicers, robotics manipulators.

Thinking about today's launches rate, these figures does not seem realistic and even with a launch per week it would take tens of years to bring SBSP space segment on orbit. So to make such a project feasible in a couple of decades, new launches capability seems are necessary.

3 Direct Solar Reflectors design

Direct Solar Reflectors architecture is in its principle quite simple and is composed of:

A large solar reflector, which aims to collect the solar flux in orbit and to redirect it towards Earth solar power plant. For lower altitudes, it can be worth to focus the beam with a parabola shaped mirror of a focal length equal to the altitude.

A platform, hosting the solar reflector payload and the main subsystems: AOCS, EPS, structure and thermal.

In order to avoid drag force effects lowering the orbit and generating torques de-pointing the platform, it is not reasonable to consider place LEO DSR below 800 km. Even at 890 km for a 1 km diameter reflector of about 15 t, the yearly cost to compensate the altitude decay is of about 540 kg of Xenon.

The structure considered for large reflectors was inspired by literature survey led in the previous phase of the study. In our case we envision a large spiderweb shape structure based on the assembly and/or 3D printing of beams which could also be inflatable beams of several tens of meters each. Thin reflecting surfaces are deployed on this structure, kept in a parabolic shape thanks to dynamic tendons. A visual representation of this process is shown in the next image, proposed by the American company Made in Space.

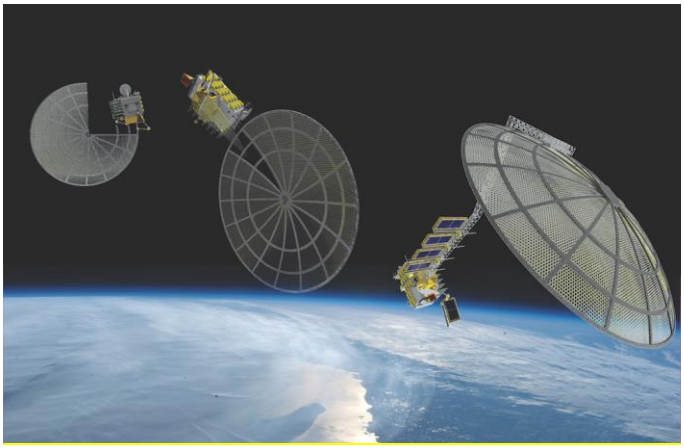
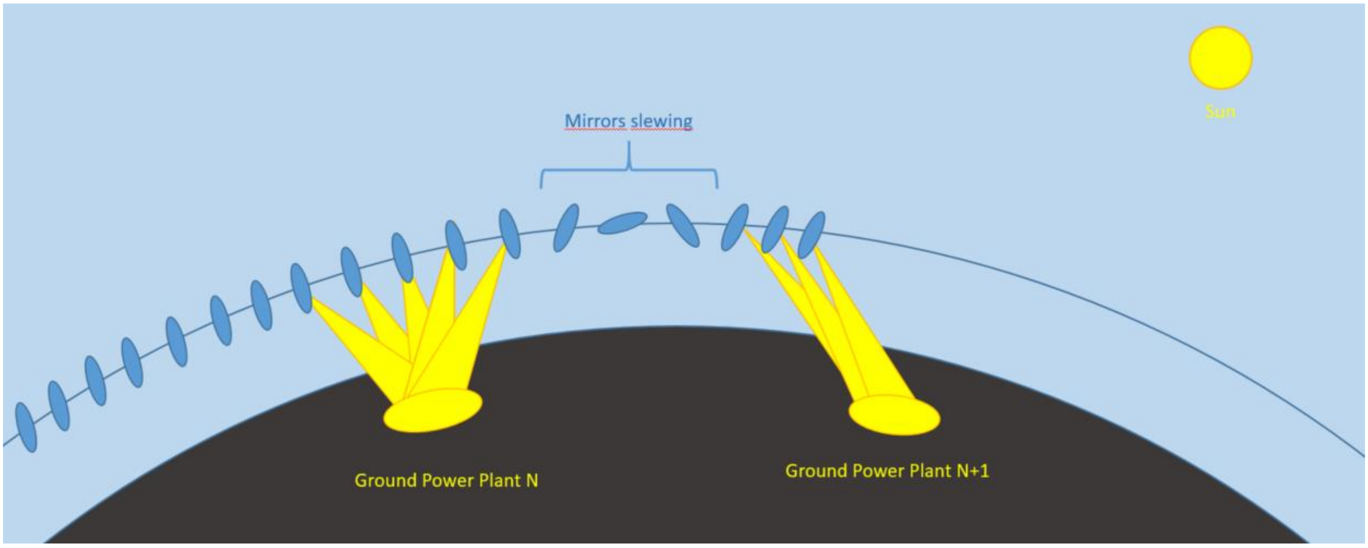


Figure 9 -In orbit 3D printing of large structures Credits: Made In Space

The attitude control shall not only ensure the stable pointing towards the ground power plant but also ensure slew manoeuvres avoiding to direct the beam towards exclusion zones while performing slew to reach the next ground power plant. This is a major constraint as it implies an important angular acceleration for a large structure.



Reaction Wheels Subsystems (RWS) actuators involving many (1000) large (100 Nms, 0.2 Nm) reactions wheels dispatched on the structure looked appealing at first glance, particularly because of its soft control distributed all over the platform preventing its bending. But this option was discarded given the too low torque and angular momentum available, leading to too slow slews. And so even with more than 1000 reaction wheels. Not to mention the additional weight (12 t) and power consumption (150 kW) of such a control system.

A more preferable option is to replace RWS by several (hundreds) of CMGs similar to the ones used in the ISS (4760 Nms, 258 Nm), but the overall mass and power consumption are still of concern.

Moreover these solutions would imply an additional mean for unloading (magneto-torquers, thrusters or gravity gradient) would increase the mass or the architecture complexity.

A promising option is to use hundreds of electrical thrusters, accommodated on the edge of the large structure to generate a high torque. The advantage is that they could also be used for orbital manoeuvers. The counterpart is the huge electrical power consumption (7 kW per thruster) and also Xenon consumption. A complete slew from one power plan to the other could last about 20 min.

In conclusion, no ideal attitude control solution has been found so far. This is a point to be further analysed considering more innovative solutions such as magneto-torquing and/or gravity gradient at large scale.

Each SPS follows the four following steps:

- Ground tracking phase. In this phase the reflector is steered to redirect sunlight to a GPS for the entire duration of the pass.

- Idle phase. When the reflector is not tracking a GPS, its attitude must be changed to avoid reflecting sunlight to unwanted ground areas.

- Reorientation phase. This phase represents the transition between the ground tracking phase and the idle phase.

The Idle phase is reduced at the maximum in order to maximize the number of ground stations illuminated. However, the precise slew will depend on the precise location of the GPS. The orientation phase is currently designed with a "flip" of the SPS to avoid any illumination on Earth. However, as the power transmitted by SPS is very low (<15W/m2), the reorientation phase track could potentially be optimized to reduce the time of change (~20' today) and the propellant used

The preliminary strategy for slew motion is to avoid ground illumination. It is shared that the mointing mode is not optimal in term of AOCS. Impact will be analyzed during next phase.

4 Solar Pumped Laser design

Solar Pumped Laser design is mainly composed of:

A large solar reflector, of dimensions and design very close to the one used in LEO DSR described above, but with a much shorter focal, making the Sun’s image very small to cope with the collector size. It also could have a special surface coating in order to only reflect wavelengths about 1064 nm at which the pumping works and then minimize unnecessary incident light power onto the collector.

A collector, consisting in a lens collecting large reflector light and feeding the laser pumping cavity. For a 1 km diameter reflector, the collector lens could be made of a large fused silica aspheric lens.

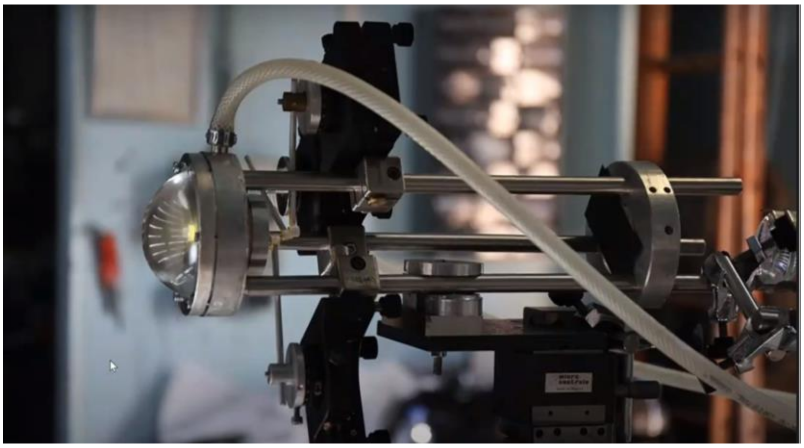


Figure 10 - Collector (spherical lens) Credit Universidade NOVA de Lisboa

A laser pumping cavity, is the place where coherent light is generated. Its material will drive the output wavelength. In our case we could consider Ce:Nd:YAG rods within a conical pump cavity which will produce a 1064 nm beam. This wavelength is interesting in our application because of the high (more than 92%) transmission of the atmosphere, minimizing the atmospheric loss. Depending on the cavity composition, this part can be very fragile and if there is no possible design to increase its lifetime, spare parts and replacement procedure should be necessary.

A telescope, to increase the gain of the laser beam generated by the pumping cavity placed in its focal point. The larger its diameter is, the lower its divergence angle is. Consequently, the sizing of this element allows to play on the spot size for a given distance to ground system, but not on the total flux transmitted which is depending on the reflector size. Several telescope types could be considered, but if possible, a single mirror telescope with a focal point outside of the aperture would advantageously avoid the use of a secondary mirror exposed to the direct laser beam.

Ideally, these four optical elements could be gathered and accommodated on a single platform composing a unitary component of a fleet of GEO Solar Pumped Lasers.

In addition to these fundamental optical elements, given the power received by collector, pumping cavity and telescope, a thermal dissipation system is necessary, with certainly high performance pump systems and hundreds of m^2 of radiators. These elements shall be sized in the next step of the study if this architecture is selected.

Finally, as for Direct Solar Reflector solution, Solar Pumped Laser platform will need an AOCS, EPS and structure.

As opposed to AOCS in LEO DSR, GEO SPL will not have to perform slews to direct the beam from one ground power plant to another, but to remain steadily pointed toward a single permanent ground power plant. The exception is for its large solar reflector part that will have to follow the slow motion of the Sun, like solar arrays do for geosynchronous satellites.

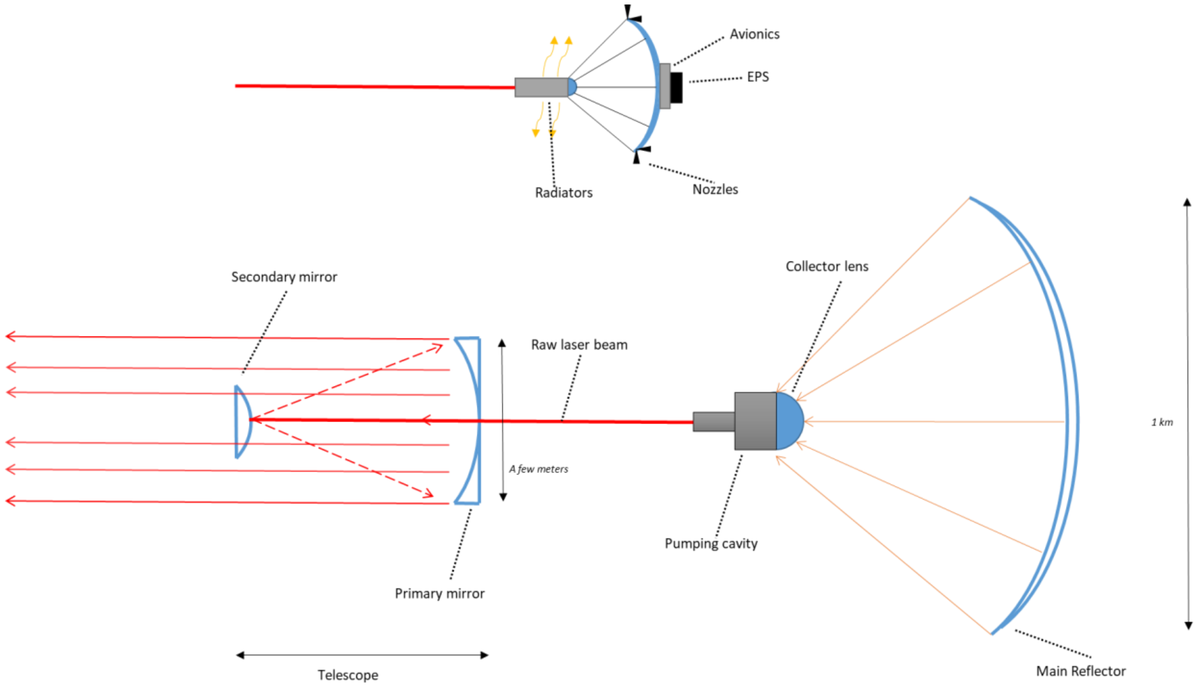


Figure 11 - Conceptual view of the GEO SPL

For orbital control, each platform will have to remain in its GEO slot, which implies a yearly delta-V of about 52 m/s. Because of their efficiency and their soft thrust to avoid structure excitation, electrical thrusters are considered. Therefore, for a mass of 25 t for the SPL platform, it typically results in a yearly consumption of 80 kg of Xenon. (52 m/s deltaV, 25 tons, with very conservative Isp of 1660s)

However, it is important to highlight that with such a system, several ways can be imagined to stop the beam generation almost immediately, as opposed to the DSR. For example, removal of the collector or redirection of the laser beam out of the telescope mirror would instantly interrupt the beam towards Earth.

5 End of life and dismantling

In this part we will list and describe the different possible strategies for end of life and then assess how it could apply to the SBSP space segment.

- **No end of life, maintained forever**. This solution seems obvious: can't we exploit SBSP for much more than 30 year after so many energy spent to make it work? The cost for that is to maintain in operational conditions the system. However it is not really satisfying as one day or another a new power production will certainly be more efficient than SBSP, like nuclear fusion.

- **Design for recycling/refurbishing**. In this approach, the space segment is designed to be recycled or refurbished in space. Used parts car be dismantled and stored in a space warehouse waiting for recycling. The recycling space factory could use solar power to melt, separate and transform materials, for example in a centrifugal solar furnace. Design for recycling supposes that the space segment uses only recyclable materials in its conception and its architecture will ease the dismantling process.

- **Decommissioning and place in a graveyard orbit**. This is a classical approach in which after operational life, the spacecraft is placed, by itself or thanks to a space tug, to an orbit on which it could not interfere with current or future mission. The definition of graveyard orbits is subject to change and it is hard to anticipate what could still be allowed in several decades.

- **Dismantling and cargo return to Earth**. This approach consists in dismantling the space infrastructures and take them back on Earth in the cargo bay of reusable upper stages which otherwise would have returned empty. It implies a considerable spent of energy but this is the cost for a much more virtuous space usage than simply burning things in the atmosphere.

- **Natural orbit decay and burn in atmosphere**. This is also a today practice but it is not sure to be still allowed in the future due to sanitary reasons (in cause the small particles spread in the atmosphere during re-entry burn). However this solution is simple for large and lightweight platforms like reflectors for which the drag force acts significantly in LEO.

The table below presents the assessment of how these end of life strategy would apply to LEO DSR and GEO SPL. Red is not applicable, green fits well, orange is feasible but not optimal.

	Applicability	
End of Life solution	**LEO Direct Solar Reflection**	**GEO Solar Pumped Laser**
No end of life, maintained forever	Maintenance cost in LEO could be prohibitive	Important cost of GEO maintenance
Design for recycling/refurbishing	Good for sustainable space but implies under optimization of the design	Good for sustainable space but implies under optimization of the design
Decommissioning and place in a graveyard orbit	LEO too crowded to remain there	Low cost solution. GEO+300km graveyard orbit will certainly remain forever
Dismantling and cargo return to Earth	Energy spent but virtuous	GEO to far for returning on Earth
Natural orbit decay and burn in atmosphere	Very easy but not the most vertuous	GEO to far for returning on Earth

Figure 12 - EoL strategies applicability to SBSP space segment

A reasonable solution seems to exploit SBSP much longer than 30 years (e.g. 60 years) while designed for recycling until it will be replaced by a more efficient system.

6 Technology maturation needs

So far, the following list of technology maturation needs were identified.

- Long duration efficient energy storage (Lithium-Sulphur battery, enhanced fuel cells)
- Additive manufacturing of large structures
- Large structure attitude control
- Solar Laser Pumping in space
- Shape control of large converging thin mirrors
- End of life management and dismantling

A detailed maturity evaluation will be provided in parallel of this technical note.

7 Annexes

Table for trade-off

Requirement for this table: The constellation of reflectors shall be able to provide when possible 4 hours of additional solar illumination at 1000W/m² per day (2h on the morning, 2h on the evening).

1. First orbit : SSO ground repeat at 888.32 km altitude, 14 revolution around Earth for one Earth revolution

Spot size at 90° of elevation	Spot minor axis [m]	Spot major axis [m]	Spot surface [m²]
	8 248	8 248	53 425 561

Key values for each line of the table below

- Available power in min spot: **53,423,971,068 W**
- Total PV power generated in min spot: **11,382,484,486 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **90 stations**

Mirror Diameter (m)	Number of mirrors in visibility	Total number of mirrors*
200	3 740	78 530
300	1 664	34 892
400	936	19 626
500	600	12 568
600	417	8 719
700	306	6 400
800	235	4 901
900	185	3 871
1000	150	3134
1200	105	2 183
1400	77	1 596
1600	59	1219
1800	47	964
2000	38	778

*As, at this altitude, the seasonal illumination has a significate impact, so the number of satellite could be here multiplied by 2 in order to have coverage on mornings and evenings. One part of the cluster will be phased for winter illumination, the other part for summer. To be refined with latitude optimisation.

**Note: there is a maximum of 140 stations to be placed along the 24h ground track (zenith passage) if we consider 4000 km distance between two stations.

2. Second orbit : SSO ground repeat at 1676.49 km altitude, 12 revolution around Earth for one Earth revolution.

Spot size at 90° of elevation	Spot minor axis [m]	Spot major axis [m]	Spot surface [m²]
	15 565	15 565	190 288 251*

*We can here question the realism of such an installation knowing that, at the moment, the world's largest photovoltaic power station is Bhadla Solar Park with 56 km². And if feasible, what would be the environmental impact of such an installation?

Key values for each line of the table below

For a mirror diameter d=[300m-1800m]:

- Available power in min spot: **190,307,271,372 W**
- Total PV power generated in min spot: **41,099,514,443 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **13 stations**

For a mirror diameter d=2000m:

- Available power in min spot: **190,288,217,193 W**
- Total PV power generated in min spot: **40,545,878,349 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **13 stations**

Mirror Diameter (m)	Number of mirrors in visibility	Total number of mirrors*
200	Arc length between **2 mirrors < 2*R_m**** *(where R_m is the radius of the mirror)*	
300	5 750	67 748
400	3 134	36 920
500	2 006	23 628
600	1 393	16 406
700	1 024	12 053
800	784	9 228
900	619	7 289
1000	502	5 904
1200	349	4 099
1400	256	3 010
1600	196	2 303
1800	155	1 819
2000	126	1 474

* The seasonal illumination seems to have an impact at this altitude also. The total number of mirrors has NOT been doubled here, as this phenomenon has not been verified at this altitude. To be refined with latitude optimisation.

** In other words, the number of satellite per cluster is too high, it cannot fit within the visibility arc of the ground station at the given altitude (at 1676.49 km of altitude, the arc length of the orbit for which the satellite is in visibility of the ground station with 30 of minimum elevation is 4 699 km).

3. Third orbit: SSO ground repeat at 2719.87 km altitude, 10 revolutions around Earth for one Earth revolution.

Spot size at 90° of elevation	Spot minor axis [m]	Spot major axis [m]	Spot surface [m²]
	25 253	25 253	500 847 377*

*We can here question the realism of such an installation knowing that, at the moment, the world's largest photovoltaic power station is Bhadla Solar Park with 56 km². And if feasible, what would be the environmental impact of such an installation?

Key values for each line of the table below

For a mirror diameter d=[400m-1800m]:

- Available power in min spot: **500,846,961,531 W**
- Total PV power generated in min spot: **117,061,484,390 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **4 stations**

For a mirror diameter d=2000m:

- Available power in min spot: **500,847,323,978 W**
- Total PV power generated in min spot: **106,842,124,129 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **5 stations**

Mirror Diameter (m)	Number of mirrors in visibility	Total number of mirrors*
200	Arc length between 2 mirrors < 2*R_m** *(where R_m is the radius of the mirror)*	
300		
400	12 662	96 664
500	5 003	38 187
600	3 474	26 516
700	2 552	19 480
800	1 954	14 913
900	1 544	11 783
1000	1 251	9 544
1200	862	6 628
1400	638	4 868
1600	489	3 727
1800	386	2 944
2000	313	2 383

* The seasonal illumination seems to have an impact at this altitude also. The total number of mirrors has NOT been doubled here, as this phenomenon has not been verified at this altitude. To be refined with latitude optimisation.

** In other words, the number of satellite per cluster is too high, it cannot fit within the visibility arc of the ground station at the given altitude (at 2719.87 km of altitude, the arc length of the orbit for which the satellite is in visibility of the ground station with 30 of minimum elevation is 7 182 km).

4. Second orbit : SSO ground repeat at 4183.54 km altitude, 8 revolution around Earth for one Earth revolution.

Spot size at 90° of elevation	Spot minor axis [m]	Spot major axis [m]	Spot surface [m²]
	38 842	38 842	1 184 944 440*

*We can here question the realism of such an installation knowing that, at the moment, the world's largest photovoltaic power station is Bhadla Solar Park with 56 km². And if feasible, what would be the environmental impact of such an installation?

Key values for each line of the table below

For a mirror diameter d=[600m-2000m]:

- Available power in min spot: **1,184,886,455,437 W**
- Total PV power generated in min spot: **258,544,910,040 W**
- Number of stations for 750 TWh yearly (with perfect meteo)**: **2 stations**

Mirror Diameter (m)	Number of mirrors in visibility	Total number of mirrors*
200	Arc length between **2 mirrors < 2*R_m**** *(where R_m is the radius of the mirror)*	
300		
400		
500		
600	15 472	80 676
700	6 104	31 826
800	4 403	22 954
900	3 479	18 136
1000	2 818	14 690
1200	1957	10 201
1400	1438	7 494
1600	1101	5 737
1800	870	4 532
2000	705	3 672

* The seasonal illumination seems to have an impact at this altitude also. The total number of mirrors has NOT been doubled here, as this phenomenon has not been verified at this altitude. To be refined with latitude optimisation.

** In other words, the number of satellite per cluster is too high, it cannot fit within the visibility arc of the ground station at the given altitude (at 4183.54 km of altitude, the arc length of the orbit for which the satellite is in visibility of the ground station with 30 of minimum elevation is 10 495 km)