# Recommendations for Sub-Scale Demonstrator Mission

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# SBSP Pre-Phase A System Study

# Recommendations for Sub-Scale Demonstrator Mission

**DRL: TN 5**

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# Change Records

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# 1 Introduction

## 1.1 Scope and purpose

The main objective of an SBSP to be addressed by the relevant demonstrator mission is to prove the feasibility of collecting solar energy in space and transmitting it to Earth for use as a renewable energy source.

This document describes the functions and technologies to be addressed by the demonstrator mission. It provides essential recommendations based on technical considerations, along with an initial system size estimate derived from a dedicated parametric model.

## 1.2 Applicable documents

| Internal code / DRL | Reference | Issue | Title | Location of record |
|---|---|---|---|---|
| [AD1] | | | Orbit Analyses for Commercial-Scale Space-Based Solar Power Systems | |
| [AD2] | | | ESSB-HB-U-005 Space system Life Cycle Assessment (LCA) Guidelines iss.1.0 | |
| [AD3] | | | ESA LCA Database | |
| [AD4] | | | ECSS-U-AS-10C Rev.1 – Adoption Notice of ISO 24113: Space systems – Space debris mitigation requirements (3 December 2019) | |
| [AD5] | | | Study Report(s) from ESA Future Launchers Preparatory Programme activity titled “euroPean Reusable and cOsT Effective heavy lIft transport investigation” (PROTEIN) | |
| [AD6] | | | ESA-TECSF-SOW-2022-003590 - Statement of Work Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power (SBSP) System for Terrestrial Needs | |

## 1.3 Reference documents

| Internal code / DRL | Reference | Issue | Title | Location of record |
|---|---|---|---|---|
| [RD1] | | | Final Deliverables from Frazer-Nash Consultancy for ESA-funded study titled “Cost-Benefit Analysis of Space-Based Solar Power Generation for Terrestrial Energy Needs” https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html https://esamultimedia.esa.int/docs/technology/frazer-nash-consultancy-SBSP-cost-benefit-study-full-deliverables.zip | |
| [RD2] | | | Final Deliverables from Roland Berger for ESA-funded study titled “Cost-Benefit Analysis of Space-Based Solar Power Generation for Terrestrial Energy Needs” https://esamultimedia.esa.int/docs/technology/roland-berger-SBSP-cost-benefit-study-full-deliverables.zip | |
| [RD3] | | | SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project) | |
| [RD4] | | | Mankins, John C. "New Developments in Space Solar Power." NSS Space Settlement Journal (2017): 1-30. | |
| [RD5] | | | Space Solar Power: An Overview – John C. Mankins (Presentation at ISDC 2022) | |
| [RD6] | | | Cash, Ian. "CASSIOPeiA–A new paradigm for space solar power." Acta Astronautica 159 (2019): 170-178. | |

| Internal code / DRL | Reference | Issue | Title | Location of record |
|---|---|---|---|---|
| | | | https://doi.org/10.1016/j.actaastro.2019.03.063 | |
| [RD7] | | | Cash, Ian. "CASSIOPeiA solar power satellite." 2017 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE). IEEE, 2017. 10.1109/WiSEE.2017.8124908 | |
| [RD8] | | | UK Patent: GB2571383 - Solar concentrator: https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2571383 | |
| [RD9] | | | UK Patent: GB2563574 - A phased array antenna and apparatus incorporating the same https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2563574 | |
| [RD10] | | | CASSIOPEIA SPS: Advantages for Commercial Power, I Cash (Presentation at ISDC 2022) | |
| [RD11] | | | Space Solar Power development in China and MR-SPS, 4th SPS Symposium 2018, Kyoto, Japan https://www.sspss.jp/MR-SPS4.pdf | |
| [RD12] | | | Fraas, Lewis M. "Mirrors in space for low-cost terrestrial solar electric power at night." 2012 38th IEEE Photovoltaic Specialists Conference. IEEE, 2012. | |
| [RD13] | | | Fraas, Lewis M., Geoffrey A. Landis, and Arthur Palisoc. "Mirror satellites in polar orbit beaming sunlight to terrestrial solar fields at dawn and dusk." 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC). IEEE, 2013. | |
| [RD14] | | | Çelik, Onur, et al. "Enhancing terrestrial solar power using orbiting solar reflectors." Acta Astronautica 195 (2022): 276-286. | |
| [RD15] | | | Çelik, Onur, and Colin R. McInnes. "An analytical model for solar energy reflected from space with selected applications." Advances in Space Research 69.1 (2022): 647-663. | |
| [RD16] | | | ESSB-ST-U-004 ESA Re-entry Safety Requirements iss.1.0 | |
| [RD17] | | | FNC 011337 53514R Space Based Solar Power End of Life Study Final Report (Frazer-Nash Consultancy) Issue 1 | |
| [RD18] | | | FNC 011337 53615R Space Based Solar Power End of Life Study Summary Report (Frazer-Nash Consultancy) Issue 1 | |
| [RD19] | | | Sala, Serenella, et al. "Global normalisation factors for the environmental footprint and life cycle assessment." Publications Office of the European Union: Luxembourg (2017): 1-16 | |
| [RD20] | | | A. D. Couchman and A. G. Russell, "Deployable phased array antenna for satellite communication: EP 1854228", 2010-5-5. | |
| [RD21] | | | Tadashi Takano, Kenji Saegusa, Kuniaki Shibata, Yuhei Kaneda, Yasuyuki Miyazaki and Yuta Araki, "Novel Phased- | |

| Internal code / DRL | Reference | Issue | Title | Location of record |
|---|---|---|---|---|
| | | | Array Antenna with Stepped Deployment to Overcome Container Size Limitation", Acta Astronautica, vol. 192, pp. 113-121, 2022. | |
| [RD22] | | | M. Gal-Katziri, A. Fikes, F. Bohn, B. Abiri, M. R. Hashemi and A. Hajimiri, "Scalable, Deployable, Flexible Phased Array Sheets," 2020 IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, 2020, pp. 1085-1088, doi: 10.1109/IMS30576.2020.9224066. | |

## 1.4 Definitions and Acronyms

| Acronym/Abbreviation | Definition |
|---|---|
| DC | Direct Current |
| GEO | Geostationary Orbit |
| GPS | Ground Power Station |
| LEO | Low Earth Orbit |
| MEO | Medium Earth Orbit |
| PV | Photovoltaic |
| RF | Radio Frequency |
| SBSP | Space-Based Solar Power |
| SPS | Solar Power Satellite |
| SSO | Sun-synchronous orbit |
| SSPA | Solid State Power Amplifier |
| TAS | Thales Alenia Space |
| TN | Technical Note |

# 2 Proposed Functions & Technologies For The Demonstrator

When dealing with an SBSP demonstrator, it is necessary to reconsider and adapt several key functions and assumptions from the full-scale system to a sub-scale system. The aim of the demonstrator is to prove the feasibility of wireless power transmission from orbit to Earth incorporating and validating as many of the technologies of the full-scale SBSP system.

The following three primary functions of the SBSP energy chain are still valid when addressing sub-scale systems:

- Converting solar power to DC power: accomplished through PV panels;
- Converting DC power to RF power: carried out by an antenna equipped with DC-RF converters;
- Converting RF power to DC power: fulfilled by a Ground Power Station equipped with rectenna (RF-DC converters) mesh.

The first two functions are part of the SPS demonstrator platform, while the third function involves a Ground Power Station that receives the power beaming and converts it into DC power.

The three main system areas that define the SBSP sub-scale system, as for the full-scale system, are:

- PV area;
- On-board antenna area;
- GPS area.

As detailed in section 3.4.2.2 of TN3, the relationship between the on-board antenna area and the GPS area is influenced by three interrelated factors that necessitate re-evaluation for the sub-scale system:

- Orbit altitude
- Transmission frequency
- Beam collection efficiency (the proportion of the emitted power beam from the antenna that is intended to be captured on ground)

Clearly, the beam collection efficiency, as well as other efficiencies like the RF-DC conversion efficiencies, will affect the total PV area needed.

These aspects will be explored in the following sections in order to highlight the differences between the SBSP demonstrator and the full-scale SBSP system.

## 2.1 Orbit Selection

In the frame of the demonstrator mission, the key function of the system is to validate technologies trying to scale down each subsystem with the aim to reduce costs as much as possible. Startin from these considerations there are many reasons, listed below, that suggest to transition from a GEO to a LEO operational orbit:

- With no continuous baseload power transmission requirement, the orbit is not bound to the visibility time of the GPS. This allows to take advantage of any orbit with a ground-track that passes on the GPS, so it is possible to pick lower orbits w.r.t. GEO, greatly reducing the energy required to bring the SPS in its operational orbit;
- Considering that antenna area and GPS area are proportional to their reciprocal distance, reducing the orbit's altitude will allow for an overall smaller system;
- As the ground area required to capture the main lobe of the radiated RF beam depends on the elevation angle, transmitting only during the SPS passes on top of the GPS allows to minimize the GPS area.

With these considerations in mind there are two possible options for the operational orbit: a repeating SSO or a LEO orbit.

The main advantage of the repeating SSO is to always have the satellite on top of the GPS when not in eclipse and at the desired time. It is also possible to pick orbital parameters to choose the days between two equal passes. Two examples of orbital parameters are the following:

| Altitude [km] | Inclination [deg] | Repeat cycles [days] | Number of revolutions |
|---|---|---|---|
| 624 | 97.7 | 5 | 74 |
| 485 | 97.2 | 4 | 61 |

**Table 2-1 Examples of repeating SSO orbital parameters**

The main disadvantage lies in the higher amount of station-keeping and the higher energy required to bring the spacecraft in orbit w.r.t. a lower inclination orbit.

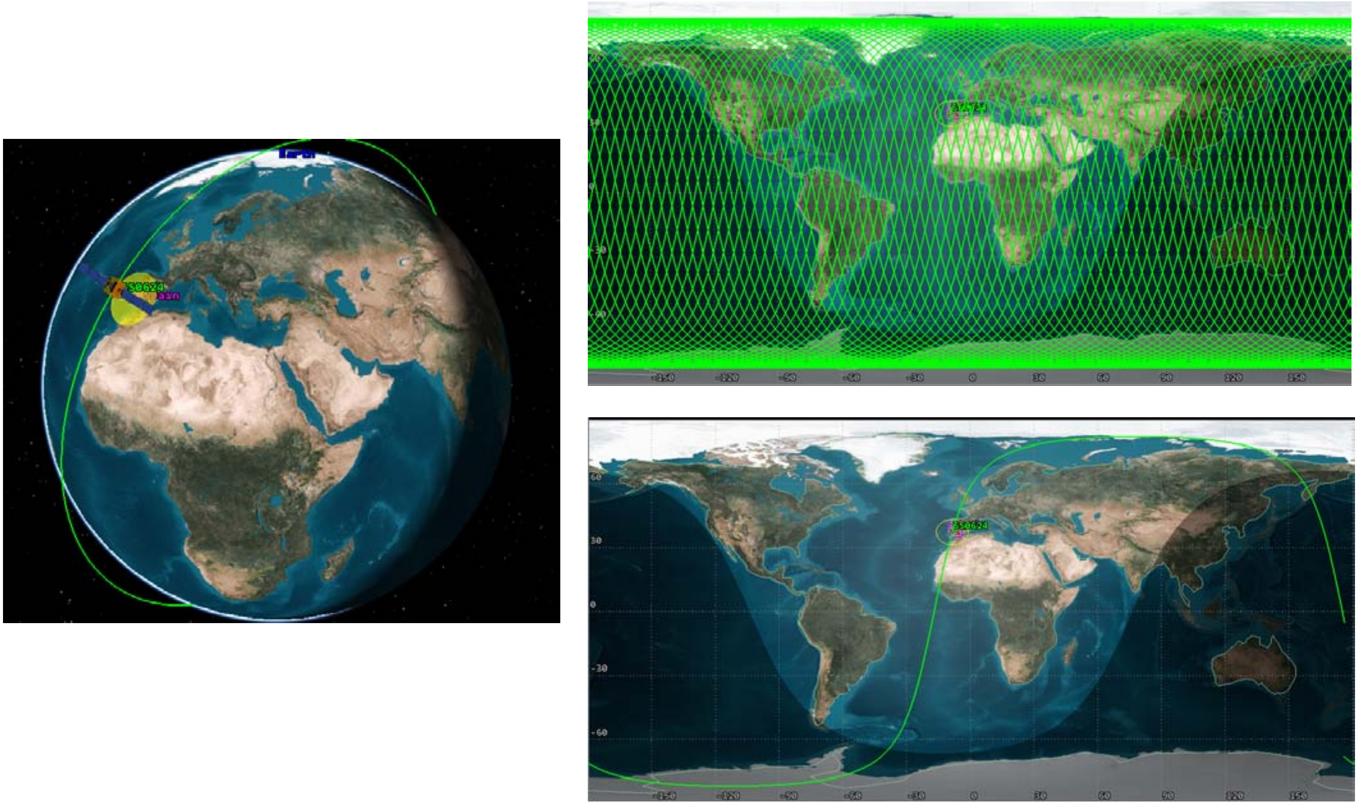
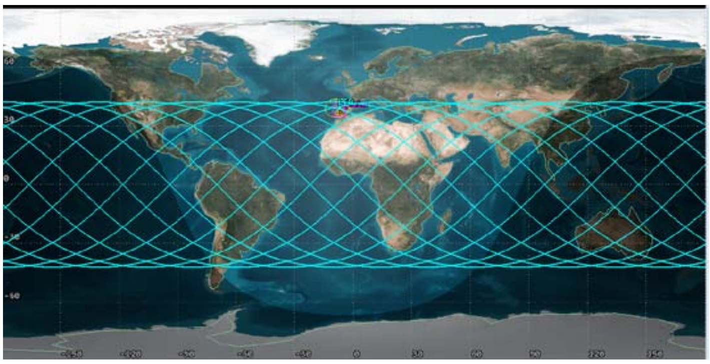


**Figure 2-1 Example of repeating SSO orbit**

Concerning the LEO orbit, the only requirement is to have an inclination at least equal to the latitude of the GPS. This in order to have the satellite on top of the GPS for at least one orbit. It is suggested to keep the idea of the repeating ground-track to ensure that the satellite will pass on top of the GPS multiple times. The main disadvantage is the possibility to have passes above the GPS during eclipse, thus having unusable passes.



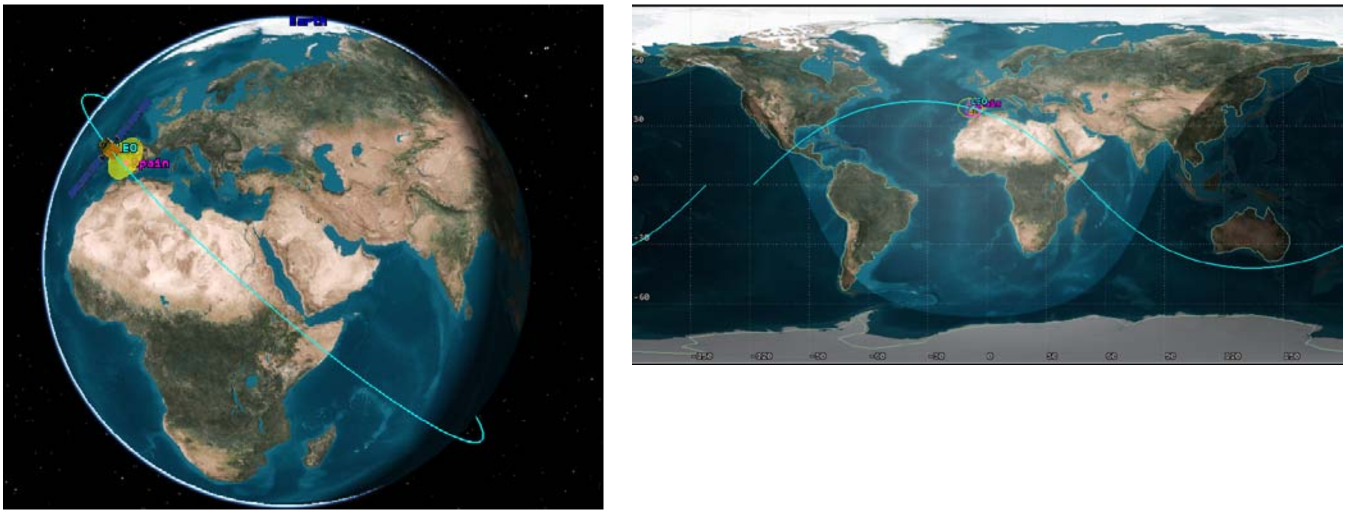


**Figure 2-2 Example of repeating LEO orbit**

Both options are feasible, so the choice will heavily depend on the demonstrator mission requirements. The orbit's altitude will depend on the required beaming time: the higher the orbit the higher the amount of beaming time per orbit.

## 2.2 Transmission Frequency

Given the shorter development timeline available for the SBSP demonstrator compared to the full-scale system, the frequency selection of 5.8 GHz (refer to section 3.4.2.5 of TN3) adopted for the full-scale system need to be reassessed.

For this assessment the projected curves for DC-RF and RF-DC conversion efficiencies need to be taken into account (e.g., rectenna efficiencies depicted in Figure 2.1). In the context of a shorter-term solution an ad-hoc frequency rationale is necessary.

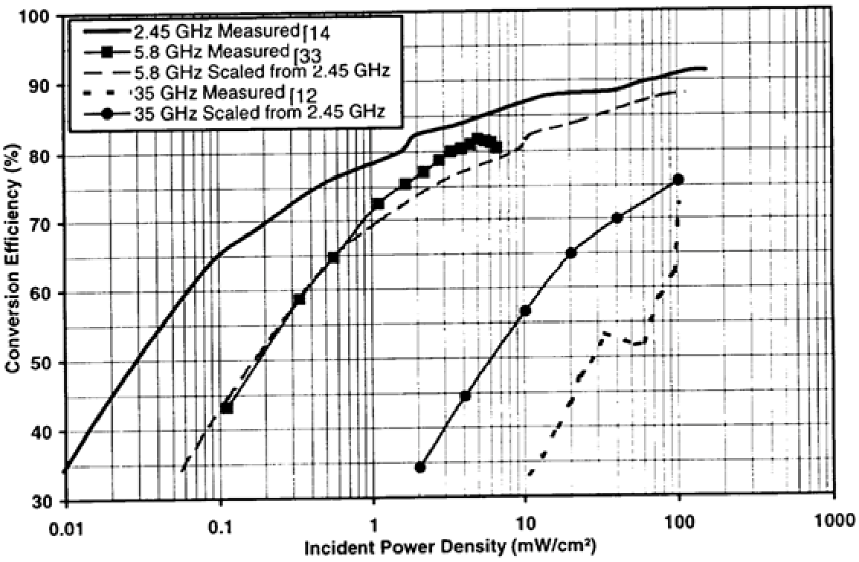



**Figure 2-3 Rectenna efficiency curves**

From a technological readiness perspective, achieving higher efficiencies is likely to be more attainable when dealing with lower frequencies than 5.8 GHz, such as 2.45 GHz.

This holds particularly true when addressing situations involving very low incident power density. As will be elaborated upon in Section 2.3, the RF-DC efficiency significantly diminishes when dealing with lower power densities, a scenario encountered in a demonstrator where reduced power levels are validated.

Furthermore, this effect becomes more pronounced when working with higher frequencies, as clearly illustrated in Figure 2-3. Hence, it is advisable, especially for an first demonstrator mission, to incorporate DC-RF technologies akin to those in the full-scale system (SSPA converters), while opting for a lower operational transmission frequency of 2.45 GHz.

## 2.3 Beam Collection Efficiency

As outlined in section 3.4.2.2 of TN3, the power beam adheres to the principles of the "Airy disk" ray-optical model. The beam's intensity is greatest at its centre and gradually diminishes as we move away from it, ultimately reaching (considering a one-dimensional view) a point where it diminishes to zero; this point is known as the first zero. Subsequently, the intensity oscillates, reaching a second zero and so on (see Figure 2-4).

Consequently, the primary (first) beam contains 83.8% of the total transmitted power, while the second beam accounts for 7.2%. The efficiency of the beam is contingent on the dimensions of the Ground Power Station and the antenna, in addition to the frequency and the distance. The intensity conforms to a diffraction pattern on the Ground Power Station.

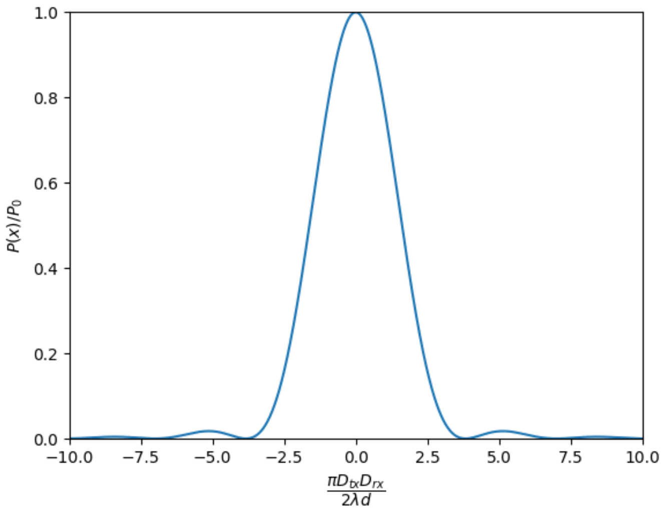



**Figure 2-4 Intensity profile due to diffraction**

When considering harnessing power up to the first null of the Bessel function (83.3% of the total power), the following formula is applicable:

Antenna_diameter * GPS_diameter = 2.44 λ d

Where λ is the wavelength (m) and d is the orbit altitude (m).

Nonetheless, the approach of capturing a specific percentage of this power beam on ground shifts slightly when addressing a lower power-level demonstrator mission. In a full-scale system, the objective is to maximize the usable percentage of the beam while adhering to the constraints of maximum (average and peak) W/m2. Conversely, in the case of an initial demonstrator with power arriving on Earth at the kW level, the challenge shifts to ensuring a sufficient average power intensity on the Ground Power Station's rectennas.

Indeed, as illustrated in Figure 2-3, the rectenna efficiency experiences a significant decline as the average incident power density decreases. This is a key factor contributing to the overall energy chain efficiency being lower in comparison to the full system.

To mitigate this effect, it is necessary to strike a balance between this efficiency and the efficiency of the power beam collection.

As depicted in Figure 2-5, when dealing with extremely low power values, having a large GPS area might seem advantageous for collecting a greater portion of the power beam. However, this approach would result in a lower average power density, subsequently leading to a decreased RF-DC conversion efficiency.

Conversely, opting for a smaller GPS area is preferable to achieve a higher average incident power density, thus enhancing the RF-DC conversion efficiency. Nonetheless, this choice implies the collection of a smaller fraction of the overall power beam.

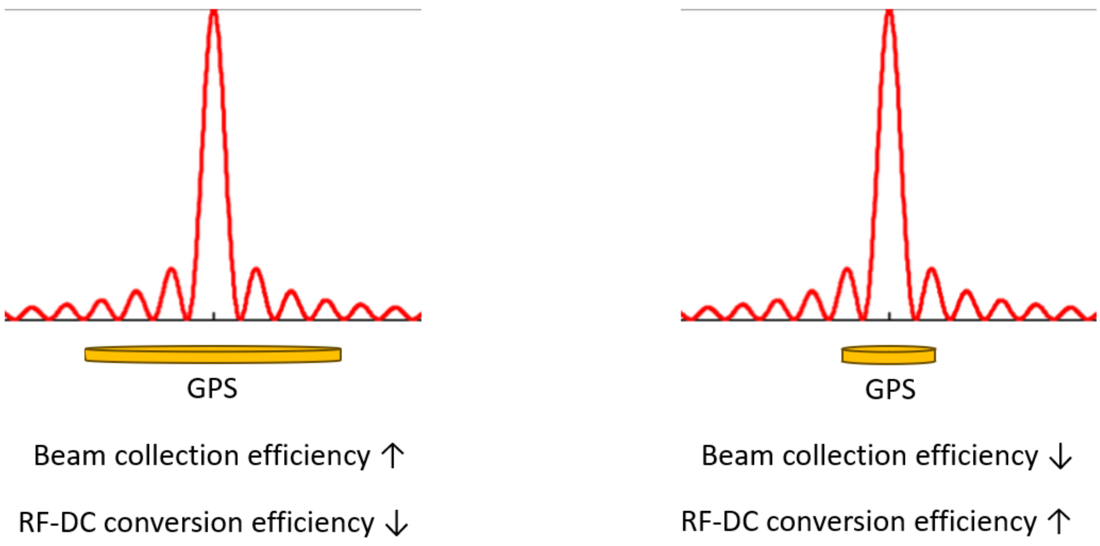



**Figure 2-5 Consequences of collecting more or less power on ground**

This line of reasoning holds true also in reverse when the Ground Power Station (GPS) area remains constant, and the selection of the on-board antenna area becomes variable. Therefore, in Chapter 3, a parametric model will be introduced, incorporating all the aforementioned considerations. This model allows to understand how, when we establish a GPS area and a desired power output to be transmitted to the ground, the decision regarding the on-board antenna area impacts the dimensions of the solar panel area. This is explained by accounting of these pivotal efficiencies that influence the overall system.

## 2.4 Other Aspects

When consideringg the shorter development timeline available for an SBSP demonstrator in comparison to the full-scale system, the following two aspects, incorporated in the parametric model, need to be considerd:

- Selection of PV cell technology for the demonstrator: when it comes to a mission closer in time, a more mature technology is essential in contrast to the Perovskite cells chosen as the baseline for the full-scale SBSP system. Consequently, conventional multijunction cells need to be considered for the demonstrator's solar panels, with a corresponding cell efficiency (incorporated into the demonstrator parametric model) of approximately 32%, in accordance with the latest values for space multijunction cell technologies (refer to the Figure 2-6). However, it is worth noting that the demonstrator could also include the option to carry Perovskite cells on board to evaluate key performance parameters and advance this technology for future integration into the full-scale mission.

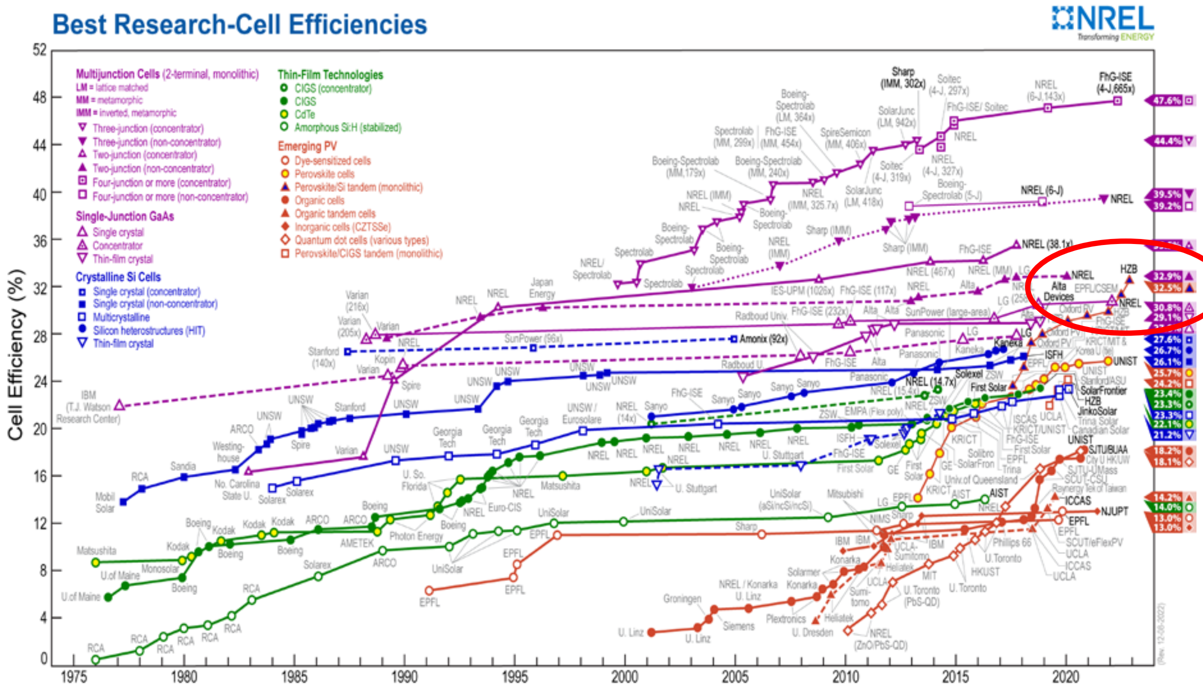



**Figure 2-6 State of art of PV cell technologies**

- SSPA efficiency: In the context of the full-scale mission, it is reasonable to contemplate expected DC-RF conversion efficiency values. However, the demonstrator mission necessitates a closer examination of the current state-of-the-art converters. Consequently, for the parametric model, it is imperative to take into account more plausible conversion efficiency values of approximately 50% and 60%, which vary depending on the transmission frequency.

# 3 Demonstrator Digital Model Results

A parametric model has been established for the SBSP demonstrator mission. This model encompasses a revised efficiency chain and incorporates all the essential formulas and system assumptions. Integrated into the SBSP Analysis Framework, this parametric model take as input a designated Ground Power Station (GPS) area and a Target Power on ground (either individually or in combination, see Figure 3-1) to generate informative curves that illustrate the relationship between onboard antenna area and solar panel area.

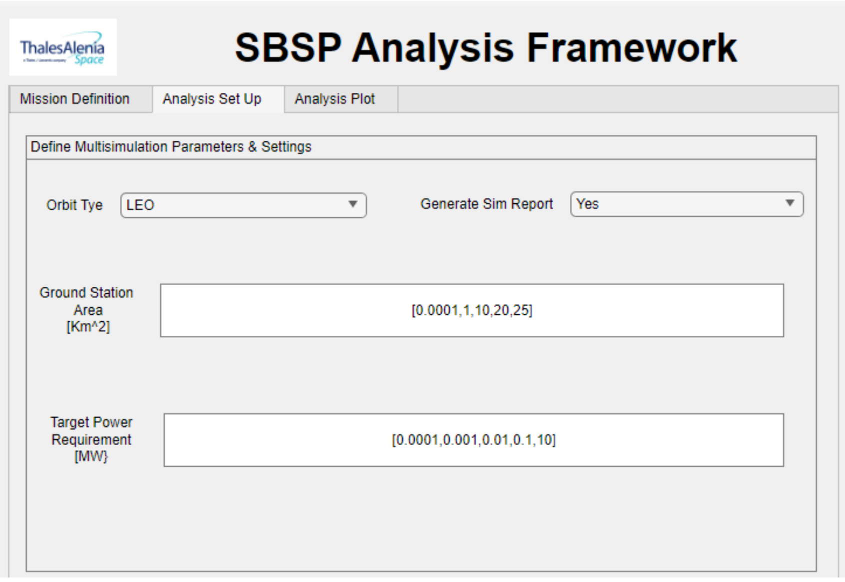



**Figure 3-1 SBSP Analysis Framework demonstrator mission scenario GUI**

Although the advantages of considering a LEO orbit for the demonstrator have been explained in paragraph 2.1, the graphical user interface allows to select the following orbit:

- LEO orbit (500 km)
- MEO orbit (20 000 km)
- GEO orbit (35 786 km)

The objective here is to gain a practical understanding of the drawbacks associated with opting for an higher altitude orbit for an first demonstration mission.

Several analyses are presented below (Fig. 3.2-3.7), each focusing on specific input that are thoroughly detailed for completeness. All the graphs are in logarithmic scale.

**Analysis 1**:

- GPS area = 10 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = LEO

**Analysis 2**:

- GPS area = 5 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = LEO

**Analysis 3**:

- GPS area = 5 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = MEO

**Analysis 4**:

- GPS area = 5 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = GEO

**Analysis 5**:

- GPS area = 1 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = LEO

**Analysis 6**:

- GPS area = 0.1 km2
- Target power on ground = [1 kW 10kW 100kW 1 MW]
- Orbit = LEO

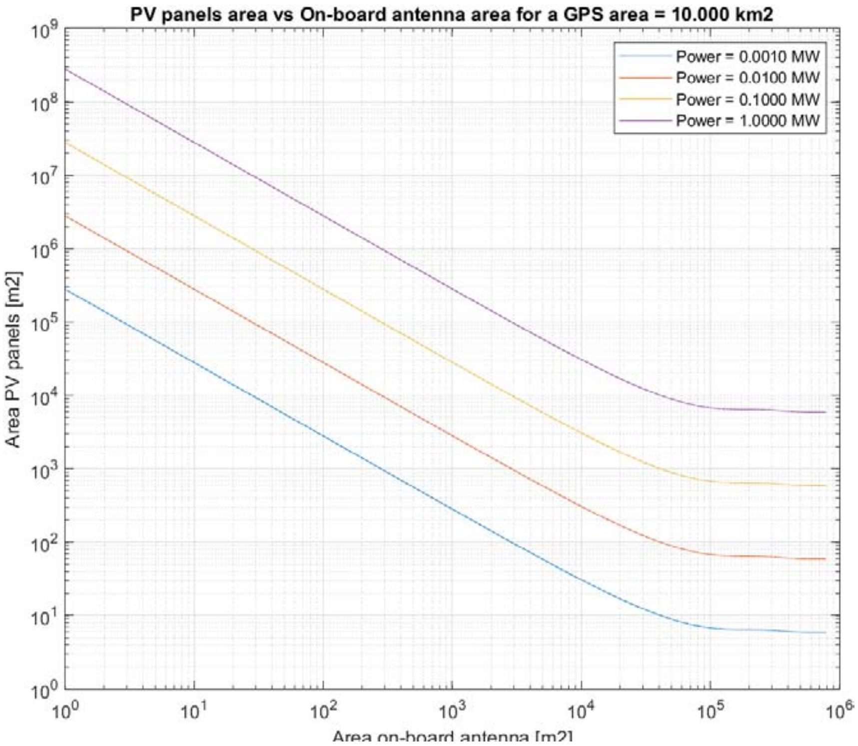



**Figure 3-2 Analysis 1 results**

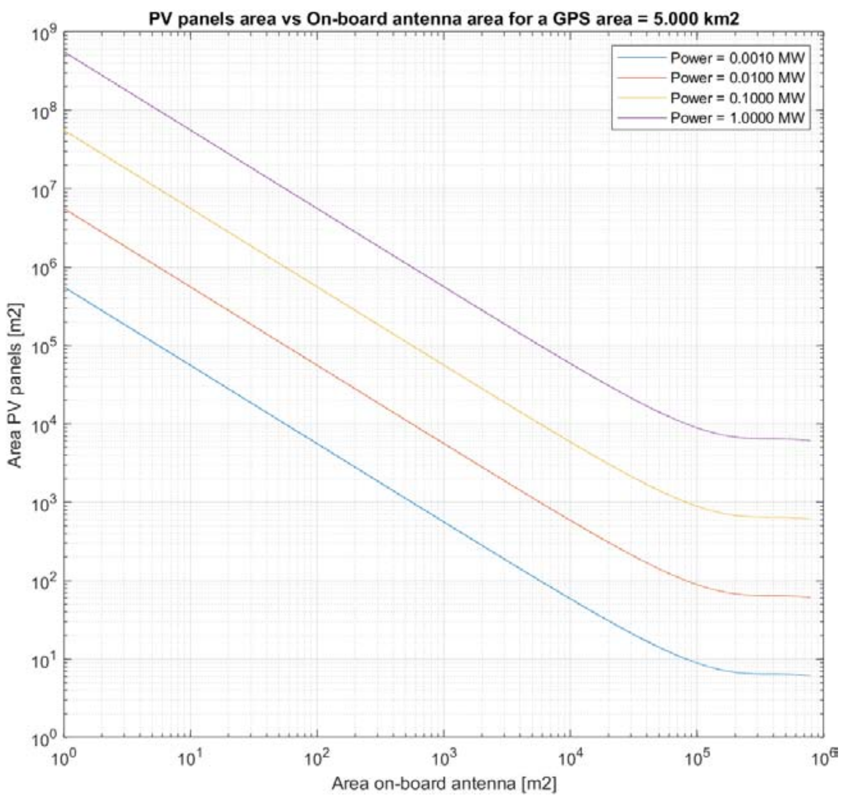



**Figure 3-3 Analysis 2 results**

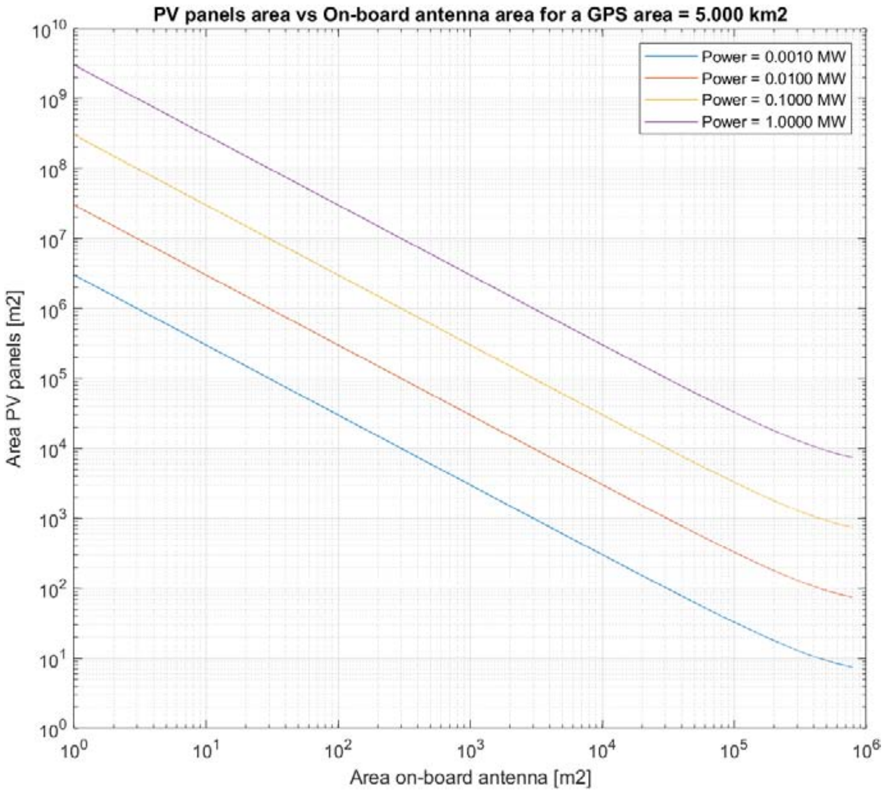



**Figure 3-4 Analysis 3 results**

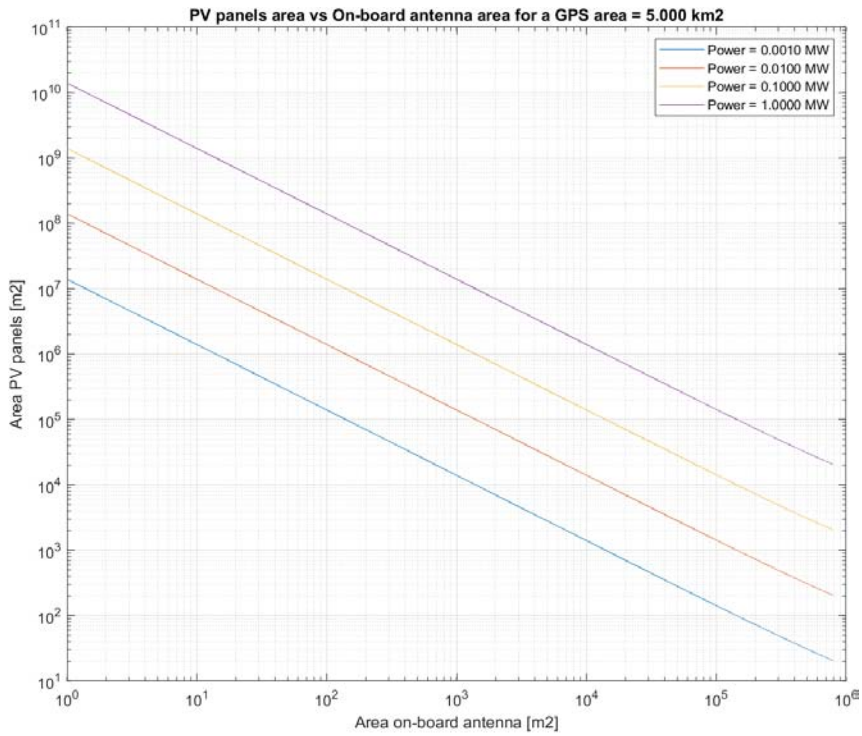



**Figure 3-5 Analysis 4 results**

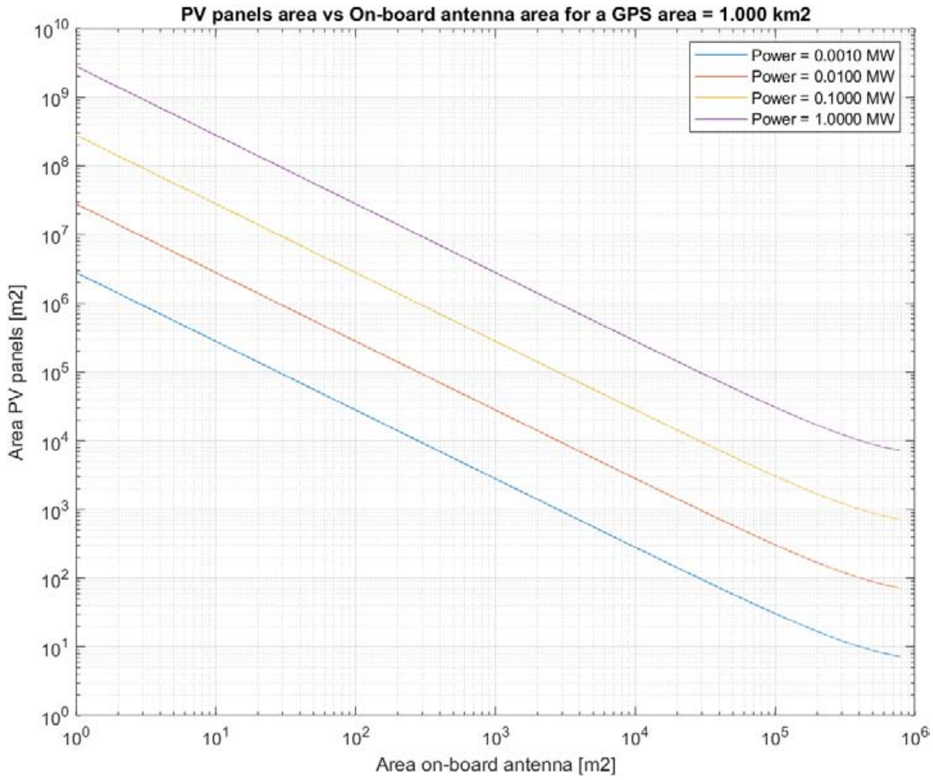



**Figure 3-6 Analysis 5 results**

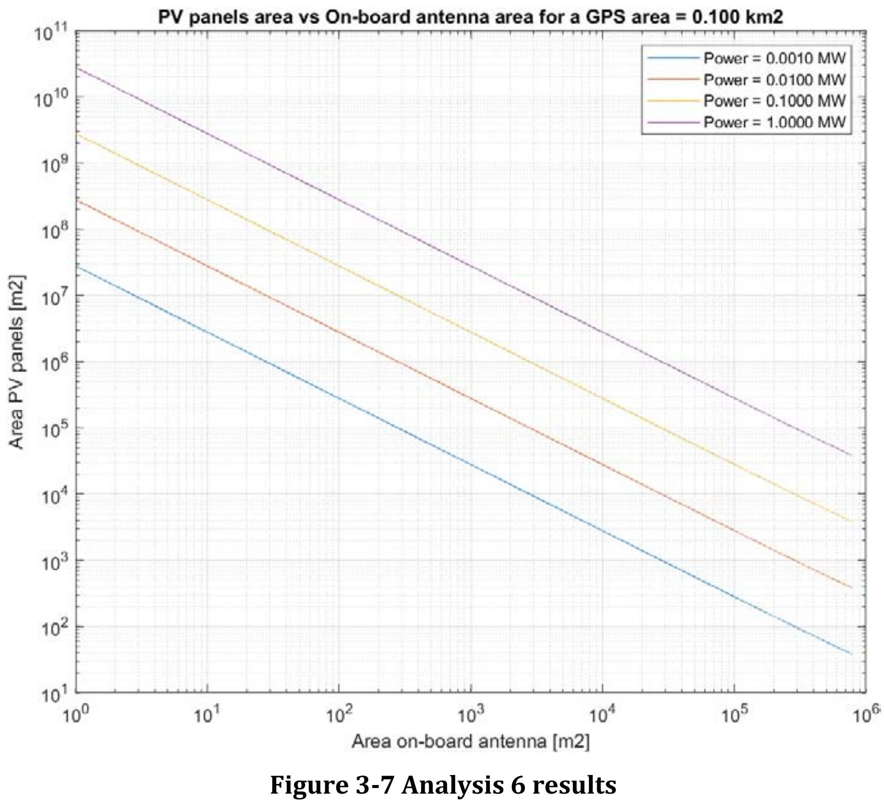



**Figure 3-7 Analysis 6 results**

Additional analyses are possible by means of the parametric model implemented into the SBSP Framework Analysis.

However, for our first SBSP demonstrator, some viable solutions have been identified considering a ground power generation capability of maximum 1 kW. The following configurations are proposed:

| Area GPS [km2] | Power on ground [kW] | Power generated in orbit [kW] | Area solar array [m2] | Area on-board antenna [m2] | On-board antenna diameter [m] |
|---|---|---|---|---|---|
| 10 | 1 | 200 | 560 | 500 | 25.2 |
| 5 | 0.5 | 200 | 560 | 500 | 25.2 |
| 1 | 0.5 | 480 | 1400 | 1000 | 35.7 |
| 1 | 0.01 | 72 | 230 | 100 | 11.3 |

**Table 3-1 Four possible demonstrator configurations**

These combinations are just examples and represent a subset of potential configurations for achieving this values of output power. The proposed solutions arise from an initial compromise involving the three primary SBSP domains: the GPS area, the PV area, and the on-board antenna area. In future studies, these values may be subject to adjustments and are presented here solely to illustrate the scale of the systems that must be considered for a demonstrator mission.

# 4 Preliminary Recommendations For The Demonstrator Mission

The demostrator allows to test various aspects of SBSP technologies, in order to assess the feasibility of their use in the full-scale system. In particular it allows to test and validate:

- emerging cell technologies, such as Perovskite, in space environment
- the power conversion performances
- the effectiveness of wireless power transmission
- the reliability of the SPS components (such as roll-out deployment mechanisms)

All of these steps are considered crucial to allow the full-scale system to be constructed and operated.

The requirements defined for the full-scale SBSP system (refer to TN1, Table 2-5) are considered valid with the exceptions of the following that are not considered applicable to the demonstrator, given the objectives mentioned above:

- UR-REQ-0010 (Commercial Utilisation) which is valid only for the SBSP full-scale system;
- UR-REQ-0060 (Target SBSP Capability) which is valid for multiple SBSP full-scale systems;
- UR-REQ-0070 (System Lifetime) which is valid only for the SBSP full-scale system;
- UR-REQ-0110 (Constant power provision) as there will be no need to demonstrate, at this stage, a baseload power provision;
- UR-REQ-0150 (SBSP fluctuation planning) considering that fluctuations are relevant only for the SBSP full-scale system;
- UR-REQ-0160 (SBSP service interruptions) considering that service interruptions are relevant only for the SBSP full-scale system.

Due to the nature of the system, many critical technologies will not be available in the timeframe of the first demonstrator satellite. One of these is probably going to be the In-Orbit assembly technologies although many studies are developing these capabilities, like TAS IOS mission. In order to be independent from other satellites, a one-launch mission is suggested for the first demonstrator mission. Using as reference the values from the 0.01 kW on ground proposed satellite in Table 3-1, it would be possible to use deployable solar panels and a foldable/inflatable phased array antenna to fit the satellite inside a single launcher fairing. The ISS ROSA demonstrates the capability to deploy large solar panels from a compact container, while many studies are tackling the concept of foldable phased array antennas as [RD20] and [RD21], which may allow to insert a 100 $m^2$ antenna in a 5 m diameter fairing (like the Ariane 6 or Falcon 9 ones). Other promising papers regarding foldable phased array sheets, like Caltech's one [RD22], may allow to reduce the volume required furthermore in the near future.

The satellite's design shall prioritize the maximization of both solar array and antenna areas in order to reduce the required GPS area. Considerations on the beam collection efficiency, as showed in Figure 2-5, will also help in reducing the GPS area, for example by collecting only the peak of the intensity profile, increasing the mean rectenna efficiency.

# 5 Conclusions

In line with the considerations reported in this document, a demonstrator mission will play a pivotal role in assessing the viability of a full-scale Space-Based Solar Power (SBSP) mission.

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