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SBSP Design Assumptions and Constraints Report

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SBSP Pre-Phase A System Study

SBSP Design Assumptions and Constraints Report

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Change Records

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1 Introduction

1.1 Scope and purpose

This document summarizes the outcome of the literature review on SBSP technologies focusing on the definition of assumptions and constraints related to the expected performances of these technologies available for SBSP deployment.

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. 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]			SIC POWER DEVICES IN POWER ELECTRONICS: AN OVERVIEW	

[RD21]			A Review of SiC IGBT: Models, Fabrications, Characteristics, and Applications	
[RD22]			Ingecon sun fsk b series 1500vdc	
[RD23]			Power Bus Management Techniques for Space Missions in Low Earth Orbit	
[RD24]			SiC Intelligent Multi Module DC/DC Converter System for Space Applications	
[RD25]			Solar Power Satellite Thermal Control Approach (E. Sacchi, G. Cassisa, M. Gottero)	
[RD 26]			Lateral GaN Schottky Barrier Diode for Wireless High-Power Transfer Application With High RF/DC Conversion Efficiency: From Circuit Construction and Device Technologies to System Demonstration	
[RD27]			J. O. McSpadden and J. C. Mankins, "Space solar power programs and microwave wireless power transmission technology," in *IEEE Microwave Magazine*, vol. 3, no. 4, pp. 46-57, Dec. 2002, doi: 10.1109/MMW.2002.1145675.	
[RD28]			R. M. Dickinson, "Magnetron directional amplifier space solar power beamer concept design," *Collection of Technical Papers. 35th Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC) (Cat. No.00CH37022)*, Las Vegas, NV, USA, 2000, pp. 1469-1479 vol.2, doi: 10.1109/IECEC.2000.870965.	
[RD29]			High efficiency RF power sources. I. Syratchev, CERN. European Physical Society Conference on High Energy Physics (EPS-HEP2019)	
[RD30]			Tierney, Brian & Rodenbeck, Christopher & Parent, Mark & Self, Amanda. (2021). Scalable, High-Sensitivity X-Band Rectenna Array for the Demonstration of Space-to-Earth Power Beaming. IEEE Access. PP. 1-1. 10.1109/ACCESS.2021.3057020.	
[RD31]			Steiner M., Bösch A., Dilger A., Dimroth F., Dörsam T., Muller M., Hornung T., Siefer G., Wiesenfarth M., Bett A.W. FLATCON® CPV module with 36.7% efficiency equipped with four-junction solar cells.	
[RD32]			Verduci, R.; Romano, V.; Brunetti, G.; Yaghoobi Nia, N.; Di Carlo, A.; D'Angelo, G.; Ciminelli, C. Solar Energy in Space Applications: Review and Technology Perspectives. Adv. Energy Mater. 2022, 12, 2200125.	
[RD33]			SAVOIR-HB-002 Issue 1 Revision 1 SAVOIR Data Handling Handbook	
[RD34]			Thermionic energy conversion for concentrating solar power, Applied Energy, Volume 208, 2017, Pages 1318-1342 (Gang Xiao, Guanghua Zheng, Min Qiu, Qiang Li, Dongsheng Li, Mingjiang Ni)	

1.4 Definitions and Acronyms

Acronym/Abbreviation	Definition
AC	Alternating Current
AM	Air Mass
AOCS	Attitude and Orbit Control System
BOL	Beginning Of Life
CASSIOPeiA	Constant Aperture, Solid-State, Integrated orbital Phased Array
CEI	Comitato Elettrotecnico Italiano
CIGS	Cu(In,Ga)Se2
CPV	Concentrated Photovoltaics
CW	Continuous Wave
DC	Direct Current
DSN	Deep Space Network
EN	European Standards
EOL	End Of Life
EPC	Electronic Power Conditioner
ESA	European Space Agency
EU	European Union
FNBW	First Null Beam Width
GEO	Geostationary Orbit
GPS	Ground Power Station
HCPV	High-Concentrated Photovoltaic
HPBW	Half Power Beam Width
HV	High Voltage
kVA	Kilovoltampere
LCA	Life Cycle Assessment
LCPV	Low-Concentrated Photovoltaic
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MJSCs	MultiJunction Solar Cells
MR-SPS	Multi-Rotary joints SPS
MV	Medium Voltage
MVA	Megavoltampere
MW	Megawatt
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
PAE	Power Added Efficiency
PCE	Power Conversion Efficiency
PSCs	Perovskite Solar Cells
PV	Photovoltaic
PVA	Photovoltaic Assembly
RF	Radio Frequency
RTG	Radioisotope Thermal Generator
SBSP	Space-Based Solar Power
SCs	Solar Cells
SSPA	Solid State Power Amplifier
SPS	Solar Power Satellite
SPS-ALPHA	SPS by means of Arbitrarily Large Phased Array
TAS	Thales Alenia Space
TRL	Technology Readiness Levels
W	Watt
WPT	Wireless Power Transmission

2 SBSP key technology critical review

2.1 Solar power generation

According to the functional analysis of the power generation and distribution chain of an SBSP plant, the Solar Power Generator of the SPS has mainly two functions:

- to collect the sunlight or heat from the Sun.
- to convert the collected sunlight or heat in electrical power.

The technologies for the electricity production are:

- Photovoltaic (PV), the Solar Power Generator is therefore an expanse of solar panels. This technology is attractive because it has good efficiency around 30% with prospects of reaching 40%. These good efficiencies can be reduced by several phenomena:
  - Variation in efficiency (voltage) as a function of cell temperature. The hotter, the lower efficiency.
  - Reduced efficiency with space radiation doses.
  - Degradation of certain photovoltaic cell technologies by UV light
  - Degradation by micro-meteors.
- Thermoelectric, the Solar Power Generator uses devices that convert the heat flux between faces in the sun and faces in the shade directly into electricity. This technology is often used in space Radioisotope Thermal Generator (RTG). Except breakthrough technology, the efficiency is low around 10%.
- PETE/HITE: Research in the field of photo-enhanced thermionic emission (PETE) and high-temperature thermionic emission (HITE) is expanding. Concentrating solar light onto PETE materials has showcased an efficiency of up to 23 and this technology could offer the advantage of operating at extremely high temperatures with a straightforward setup using concentrating reflectors. Moreover, the combination of HITE/PETE with secondary heat recovery (Stirling, Brayton or Rankine cycles) holds the potential for theoretical efficiencies surpassing 60% [RD34]. Nevertheless, when taking into account the specific mass values and technology readiness for space applications that require gigawatts of power production in orbit, these alternative technologies currently occupy a secondary position as potential solutions. Their full potential may only be realized if further development is assured in the coming years.
- Thermodynamic, the Solar Power Generator produces electricity by a thermodynamic cycle requiring boilers, turbines, generators and radiators. Several implementations are possible: Stirling, Brayton, Rankine, etc.
- Electromagnetic conversion, the sunlight is directly converted to DC by optical rectenna. An optical rectenna is a circuit containing an optical antenna the size of the light wavelength (<1µ) and a diode, which turns the light into DC electricity. Nanometric etching technologies will make it possible to create dipole antennas at visible and near infrared wavelengths. However, rectifier diode technologies do not exist at these frequencies (> 100’ THz) with significant efficiency.

We will focus on the PV electricity production by large solar panels.

2.1.1 Photovoltaic (PV) Solar Power Generator: Technology review

Solar cells (SCs) are widely recognized as the most dependable and prevalent energy generation systems utilized in aerospace applications. Presently, III-V multijunction solar cells (MJSCs) have become the prevailing commercial technology for powering spacecraft, attributed to their exceptional power conversion efficiency and certified reliability and stability during orbital operations. Nevertheless, to offset the satellite launching expenses, some spacecraft companies continue to employ more cost-effective Si-based SCs.

Moreover, in recent years, new SC technologies based on Cu(In,Ga)Se2 (CIGS) and perovskite solar cells (PSCs) have emerged as promising candidates for aerospace power systems, owing to their advantageous properties, such as lightweightness, flexibility, cost-effective manufacturing, and remarkable radiation resistance.

Typically, SCs are heterostructured devices comprising various materials stacked onto a substrate. Presently, the most commonly used light harvesters in PV technologies for space applications are Si and semiconductors used for MJSCs, including Ge, III-V semiconductors like GaAs, InP, and their alloys (InGaP, InGaAs, InGaNAs, AlInGaP, and AlInGaAs). Among these, InGaP/InGaAs/Ge 3JSCs and AlInGaP/AlIn-GaAs/InGaAs/Ge 4JSCs (produced by several companies and qualified for different space missions based on European and American Space Standards) currently set the aerospace industry's standard, as they outperform other PV technologies.

For instance, commercially available AlInGaP/AlIn-GaAs/InGaAs/Ge devices can achieve a power conversion efficiency (PCE), defined as the ratio of the electrical power produced by the SC to the incident power on the SC, of up to 32% at the beginning of life (BOL) under 1 sun AM0 illuminations, and a PCE of up to 28.7% at the end of life (EOL), i.e., after 1 MeV electron irradiation with a dose of 1015 particles cm−2, making them the top-performing space SCs.

Despite their high performance, MJSCs have some drawbacks, including rigidity, thickness (ranging from ≈80 to ≈200 μm), and weight (with a specific power of ≈0.4–0.8 W g−1 for InGaP/GaAs/Ge 3JSC, though the appropriate engineering of the metal contact can increase it to values up to 3.8 W g−1 for InGaP/GaAs/InGaAs). Additionally, they are produced through complex fabrication processes, making them prohibitively expensive.

In today's research landscape, the focus on innovative PV technologies for upcoming missions, including mega constellation programs, goes beyond merely increasing power conversion efficiency (PCE) due to higher power demands.
Researchers are also emphasizing cost reduction. To this end, more affordable production processing techniques have been proposed for single-junction devices based on Si. Lab-scale devices utilizing Si have achieved a PCE of 26.1% under 1 sun AM 1.5G illumination, making them especially attractive for short-duration missions. For instance, SpaceX's Starlink mega constellation satellites are equipped with Si solar arrays. Several companies now manufacture Si-based SCs with a PCE of 16.9% at the beginning of life (BOL) under 1 sun AM0 conditions, qualifying them for space missions.

However, Si-based SCs possess some limitations, including their non-flexible nature, heaviness (with a thickness >100 μm and a specific power of ≈0.38 W g−1), and reliance on time-consuming

and expensive production procedures. With the rising demand for more compact, lightweight, and cost-effective satellites, there is a need to explore alternative PV technologies.
In this context, Cu(In,Ga)Se2 (CIGS) thin film-based SCs emerge as a promising solution for next-generation space missions, thanks to their high radiation resistance, lightweight properties (specific power ≈3 W g−1), and the ability to be manufactured using flexible substrates through low-cost techniques, facilitating adaptation to various spacecraft shapes and streamlining design. Despite these advantages, CIGS-based SCs are not yet widely employed as power sources for satellites due to their relatively lower PCE (23.4% for lab-scale devices, under 1 sun AM 1.5G conditions).

In recent decades, another class of materials, hybrid organic-inorganic perovskites, specifically CH3NH3PbI3 (MAPbI3), has gained attention for the development of perovskite solar cells (PSCs) achieving PCE values up to 25.5% for lab-scale devices under 1 sun AM 1.5G conditions. These devices show promising potential for future space applications due to their cost-effective production through solution-processed techniques, the creation of flexible devices with low weight (with a thickness <5 µm and a specific power of 23 W g−1, the highest among all PV technologies), and exceptional radiation hardness.

An overview of the PV cells technologies for space applications is provided in Table 2-1

	Multijunction	Silicon	Cu(In,Ga)Se2	Perovskite
Efficiency	High	Medium	Medium	Medium
Lab-scale record	47.1%	26.1%	23.4%	25.5%
Commercially available for space	Up to 32%	≈17%	Not available	Not available
Radiation hardness	High	High	Excellent	High
Specific power	Low – Medium	Low	Medium	High
Specific power values range	0.4–3.8 W g−1	0.38 W g−1	3 W g−1	23 W g−1
Flexibility	Low	Low	High	High
Fabrication cost	High	High	Low	Low

Table 2-1 Overview of PV cells technologies for space applications (see [RD32])

It is worth noting that values of specific power 3.8 W g-1 for Multijunction cells are only demonstrated in laboratory environments (so have to be considered with a lower TRL with respect to conventional Multijunction cells with lower values of specific power, 0.4-0.5 W g-1, and also with lower efficiencies proved similar to Cu(In,Ga)Se2 technology).

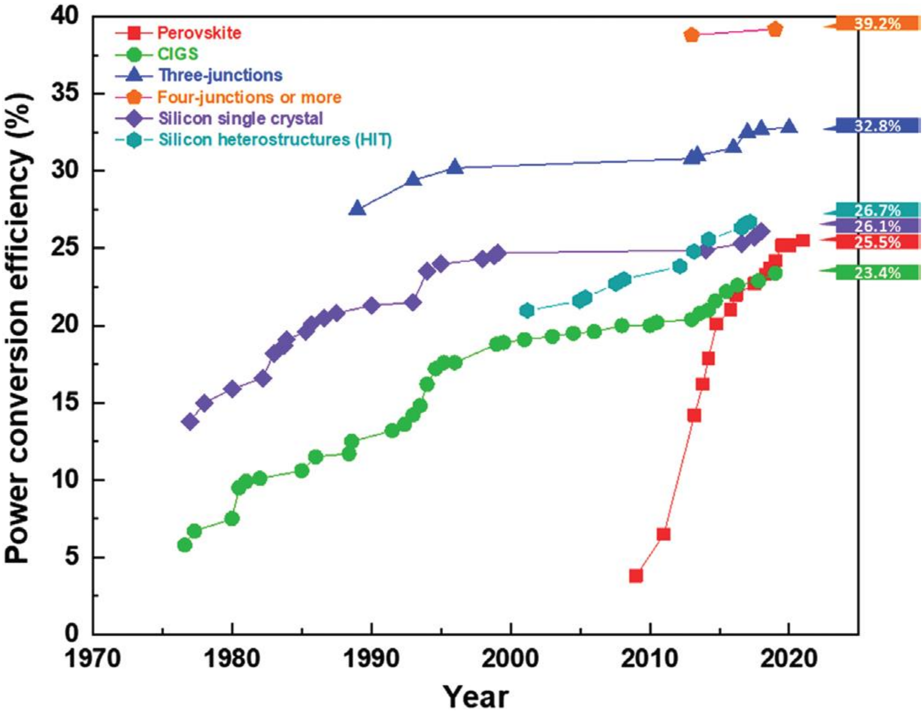

Figure 2-1 Cell efficiencies state of art (see [RD32])

The operating temperature has a strong impact on PV cell efficiency. Usually the efficiency is estimated at 25°C. The temperature effects depends on the technology and values can change from -0.5%/°C for the less performing technology to -0.2%/°C more or less for the betters. The average of a main stream technology in this moment is around -0.35%/°C. The calculation is performed with respect to the 25°C of the standard testing condition.

Concentrated photovoltaics (CPV) are widely used in combination with PV cells, employing various optical elements to concentrate light, typically sunlight, onto a central point, which is a solar cell. The use of CPV could lead to 2 main advantages :

- replacement of a part of PV cells with much lower cost lens/reflectors
- higher lab proved cell efficiencies with respect to conventional PV cells

However this technology presents also some cons such as thermal management, very high precision needed for the incident solar flux and higher overall complexity (and less reliability) of the system. The intensity of concentration is often expressed in terms of the number of Suns or ratios. When the light intensity on the solar cell surpasses 10 Suns, passive cooling of the PV cell becomes necessary, defining it as a low-concentrated photovoltaic (LCPV) system where silicon solar cells can still be utilized. If the light intensity exceeds 100 Suns, active cooling with a cooling fluid is required, categorizing it as high-concentrated photovoltaics (HCPV). The precise threshold may vary across different sources. GaAs and multilayer structures are commonly used in high-performance concentrators.

Numerous concentrator designs draw inspiration from concepts such as Fresnel lenses, reflectors, parabolic mirrors, or luminescent concentrators, each tailored to its specific application.

For instance, solar cells like InGaP/GaAs/InGaAs inverted triple-junctions are custom-made for

CPV applications, achieving an impressive efficiency of 45%. Concentrators can be specifically developed for certain types of cells and used in specialized scenarios, such as space missions. One such prototype, created by Warmann et al., utilized ultralight multilayer optical coatings to enhance the thermal emissivity of the concentrator and improve radiative transfer. This unique parabolic concentrator achieved a concentration of 15 Suns for the 1 mm wide cell.

Among the most commonly used and earliest concentrators are Fresnel lenses, which have been in use since 1979. These lenses are lightweight and capable of achieving short focal lengths and large apertures. They can be designed in circular shapes, focusing light into a point, or cylindrical shapes, concentrating light into a line, resulting in a lower concentration ratio than the circular designs. However, their optical efficiency is limited by temperature variations, leading to changes in the refractive index or deformation of the Fresnel structure due to thermal expansion.

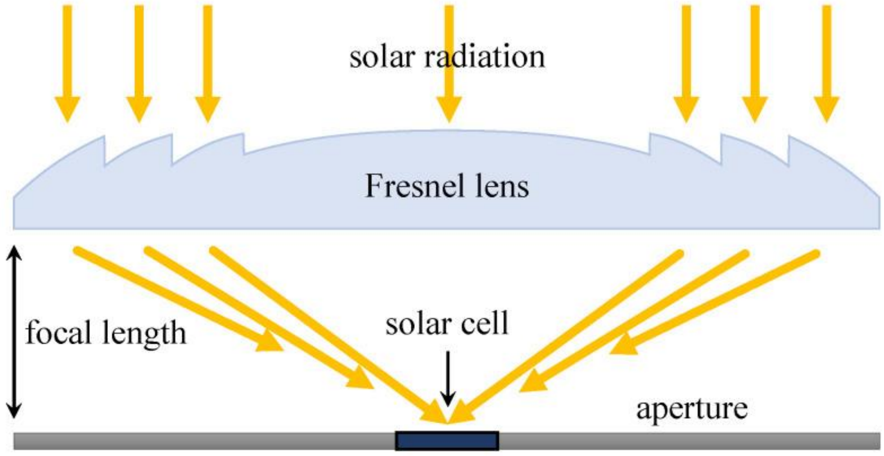

Figure 2-2 Fresnel lens concept

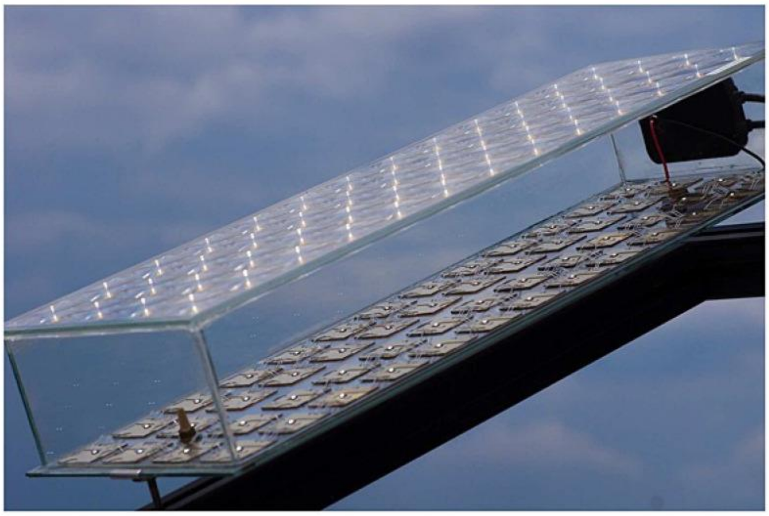

Figure 2-3 FLATCON® CPV module with 52 four-junction solar cells (see [RD31])

2.2 On-orbit power management and distribution

Once the first power generation source is set, it is necessary to define the power architecture to be implemented for managing the power transfer from the solar array to the power bus. Thus, this section looks at the main current technologies regarding power conversion in space application, which are highly demanding in terms of reliability: the related constraints of component screening set severe limits on available design solutions of regulation architectures and the materials involved.

Furthermore, modularity approach is also an important issue in space SBSP application. Therefore, technologies and architectures that make space system more agile and adaptable are covered in this section.

The main blocks representative of the power bus management are summarized in the following scheme:

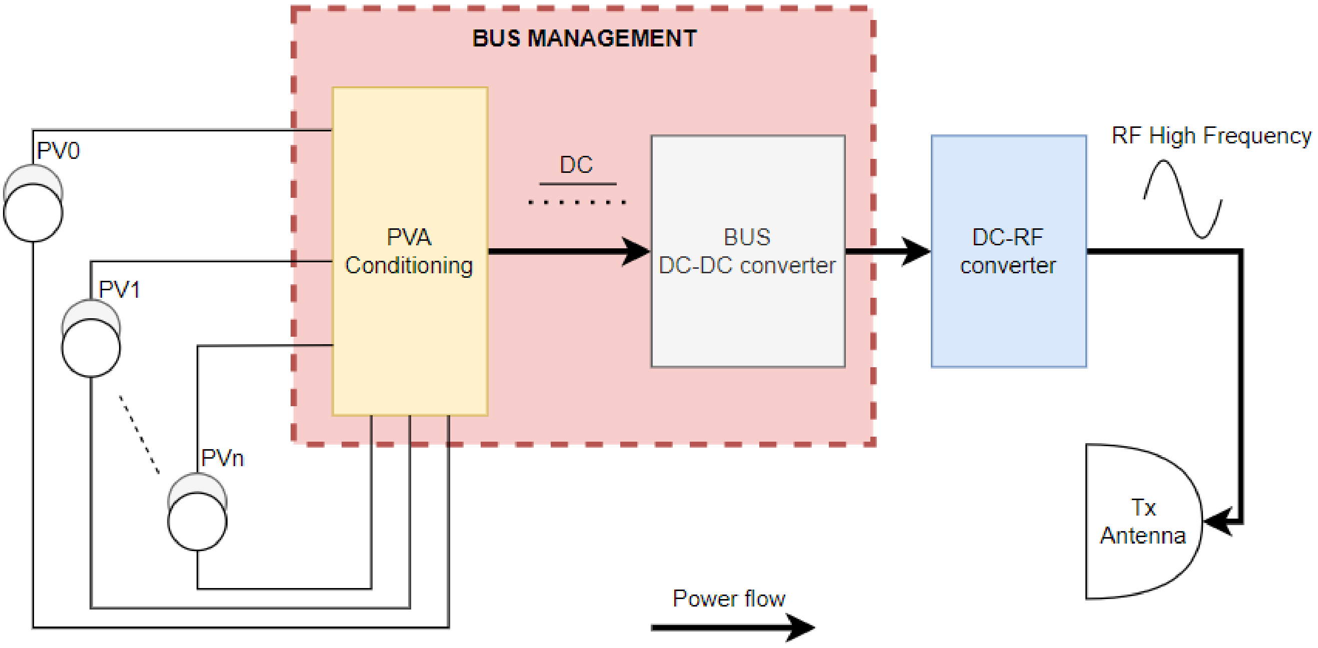

Figure 2-4 On Orbit Power management

2.2.1 PVA Conditioning

One of the main feature of the Electrical Power Subsystem is the conditioning of the power generated from the Solar Array, with the purpose of extrapolating the higher power as possible. In accordance with currently available documentation RD[23], the main approaches for this conditioning turn out to be the two listed:

1. Sequential Switching Shunt Regulation (S3R)
2. Maximum Power Point Tracking (MPPT)

The S3R is widely used because of its high power density, modularity, simplicity, and inherently high reliability. At the cost of a larger complexity, instead, the power regulation architectures implementing the MPPT techniques provide optimal energy harvesting, allowing to extract all the power available from the SA panels under different conditions (BoL, EoL, different SAA, etc.).

2.2.1.1 S3R

The S3R works by interconnecting in parallel N cells or series of PV cells that can be either directly connected-to or disconnected-from the power bus via blocking diodes. In such a configuration (Figure 2-5), each of them is also equipped with a shunt Switch able to command the shorted cell upon BUS voltage radius unification avoiding over-voltage issues.

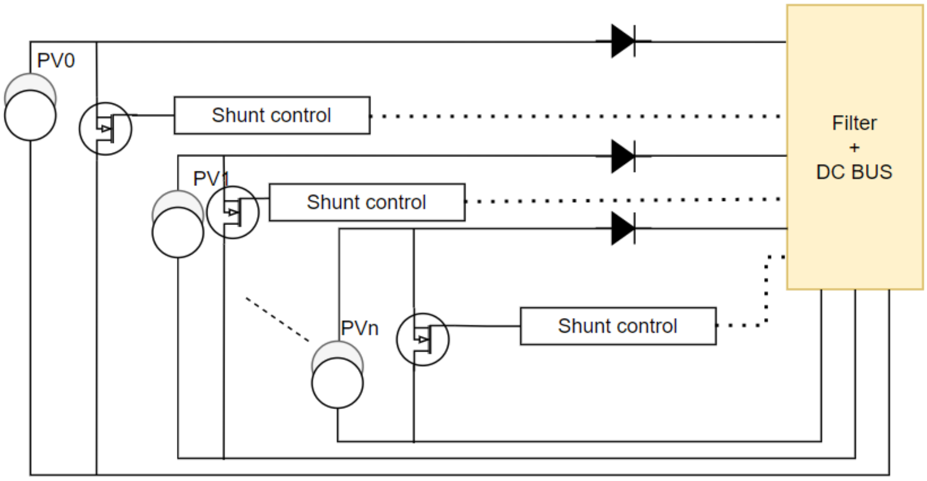

Figure 2-5 S3R schematic

2.2.1.2 MPPT

As in the previous one, also in MPPT regulation technique, the Solar Array is split into N parallel sections, not directly connected to the main Bus but via a series DC-DC converter enslaved to a controller calibrated to operate at the maximum power point of the V-I Solar Array curve.

This configuration for the Solar Array regulator is depicted in the schematic below:

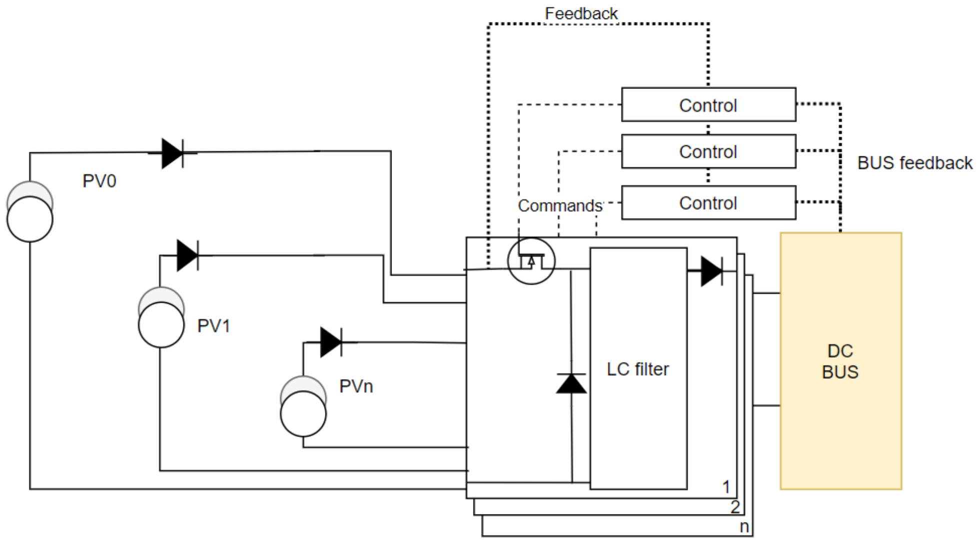

Figure 2-6 MPPT schematic

2.2.1.3 Future improvements PV management

No further crucial improvements are expected in the field of maximizing the power extrapolated from the photovoltaic panels, expect of marginal ones, i.e. performance improvements of switching components and/or algorithms. However, the more interesting aspect in terms of future improvements turns out to be the specific photovoltaic cell technology involved.

2.2.2 Harness

Assuming that each individual module takes on very high powers (order of kW - tens of kW) a big issue turns out to be the losses placed on the harness. Since it is influenced proportionally by the current flowing through the harness, it is necessary trying to work with voltages as high as possible by following the relationship:

$$I = \frac{P}{V}$$

This aspect influences the choice of the technology involved in the DC conversion. Indeed, the physics behind losses due to harnessing lies in considering the resistivity of the conductive material and the contact resistance of any connectors. In this regard, the following equations can be modeled:

$$R_{WIRE} = \rho * \frac{L}{S}$$

$$R_{contact} = \frac{\Delta V_{contact}}{I_{contact}}$$

Where:

- 'ρ' stands for the resistivity of the material, it is measured as [Ω*mm^2/m]

- L: the length of the wire expressed in [m]
- S: the cross-section of the wire expressed in [mm^2].

As for the resistance given by the connectors, it represents the dissipations given by the contact resistance on the pins.

The voltage drop and thermal issues due to dissipation, therefore, set a constraint on the maximum current that can flow through the cables and/or the use of harnesses in parallel so as to reduce the effective resistance of the connection.

Regard to this, several standards define the criteria for evaluation, qualification and subsequent selection (concerning the case study) of the harness (in this sense ECSS-Q-ST-30-11C-Rev.2, ESCC 3401 for connectors and ESCC 3901 can be mentioned).

Furthermore, by keeping into account the huge power flow involved in this specific application, the possible widespread use of rigid BusBar **custom** for connections is recommended.

For future developments regarding harness, there is no literature improvements in space-dedicated technologies.

2.2.3 Power conversion

Considering the amount of power involved, converters distributed throughout the satellite have to be provided to optimize the conversion and decrease the effective current as much as possible (so as to minimize dissipation losses on the harness).

The following section covers a comparison between the technologies currently used in space application and those that is expected to have as targets in 2050.

2.2.3.1 The actual state of the art

The converters currently used involved DC technologies so as to decrease any noise given by harmonics (which can occur in the case of AC networks). Regarding to this, considering a DC input (with a ripple) provided by the PV generation, DC-DC converters (boost type) are envisaged so as to decrease the output currents and increase the voltage. For safety reasons, galvanically isolated DC-DC converters are often considered.

For the categorization of these components, the following main construction parameters have to be taken into account:

- Efficiency 'η' which equals the ratio of output power to input power
- The working input voltage which can be limited by design factors of the converter, i.e. the use of MOSFETs or IGBTs and possibly the junctions type material
- The output working voltage and power which are also affected by the construction characteristics of the selected converter

All these quantities are influenced by the specific technology and component chosen. Another important aspect is the maximum and minimum working temperature.

2.2.3.2 Future improvements Power components

Possible technological improvements of power conversion components for space applications are mainly to be related to the development of the materials involved, that would ensure a better power efficiency.

The main materials that will be used for the junctions are:

- Gallium Nitride (GaN)
- Silicon carbide (SiC)

The type of junction provides many characteristics about the functional limits of the converter, which can be listed as given in RD[20]:

1. Band Gap Energy [eV]
2. Breakdown Field [V/cm]
3. Electron Mobility [cm^2/(V·sec)]
4. Saturation Drift Velocity [cm/sec]
5. Thermal Conductivity [W/(cm·K)]

Regarding to this a comparison between the Silicon (Si) junction and the GaN and SiC ones could be made:

- Junctions that have high Thermal Conductivity and Band Gap Energy are the best in high-temperature applications. Therefore, the SiC would perform better than GaN, and GaN performs better than Si
- Junctions with high Breakdown Field and Band Gap Energy are more suitable for high voltage applications. This means that the SiC is comparable in performance to GaN and both have vastly better performance than Si
- Junctions characterized by high Electron Mobility and Thermal Conductivity are preferred for high-frequency applications. Thus, the GaN shows better performances with respect to SiC and in turn than Si

The main characteristics of the current DC-DC converters and the ones that it is expected to have as future improvements are listed in the following table:

	Characteristics	State of the art	2050 target
Si DC/DC converter	Efficiency ‘η’	Up to 95%	-
	Voltage range	Up to 1 kV for IGBT	-
	TRL	already used in orbit	-
GaN/SiC DC-DC converter	Efficiency ‘η’	Up to 98% (SIC/GaN application)	Up to 98% (SIC/GaN application)
	Voltage range	Up to 1-5 kV (SiC,GaN MOSFET), Up 15 kV (SiC,GaN IGBT)	Up to 1-5 kV (SiC,GaN MOSFET), Up 15 kV (SiC,GaN IGBT)

	TRL	4 [RD24[1]]	9 (with adequate funding)

Table 2-2 DC-DC converter expected characteristics

2.3 Wireless power transmission

We propose here to list the available technologies for the Wireless Power Transfer system in case of a scenario based on Radiofrequency power beam. This exercise is of course not exhaustive at this stage.

According to the functional analysis of the power generation and distribution chain of an SBSP plant, the Wireless Power Transfer System of the Solar Power Satellite has mainly three functions:

- ✓ **DC to RF power conversion**: to generate RF power from the electricity provided by the Solar Power Generator.
- ✓ **Transmit Antenna**: to transmit an RF power beam toward the Ground Power Station on Earth. This function includes the formation of the power beam (spot beam) with an antenna. This also includes pointing the power beam in the direction of the location of the Ground Power Station.
- ✓ **Transmission through the atmosphere**: the power beam cross the atmosphere, which attenuates the power according to the operational frequency, the elevation of the rectennas, the geographical position of the GPS and the yearly availability.

2.3.1 Frequency selection

Frequency allocation and coordination is done by the local authorities in each country, global coordination is done by delegation to the International Telecommunication Union (ITU).

For the time being, no frequency has been assigned to this application (space to ground WPT). Nevertheless it is possible to use the bands designated for industrial, scientific and medical (ISM). Next table gives the available ISM bands.

Fmin	Fmax	Fcentre	Band	Allocation
2.4 GHz	2.5 GHz	2.45 GHz	100 MHz	Worldwide
5.725 GHz	5.875 GHz	5.8 GHz	150 MHz	Worldwide
24 GHz	24.25 GHz	24.125 GHz	250 MHz	Worldwide
61 GHz	61.5 GHz	61.25 GHz	500 MHz	Subject to local acceptance
122 GHz	123 GHz	122.5 GHz	1 GHz	Subject to local acceptance
244 GHz	246 GHz	245 GHz	2 GHz	Subject to local acceptance

Table 2-3 ISM bands

The technologies for the Wireless Power Transfer depend on the frequency of the electromagnetic signal used to transmit the power. So they are:

- Radiofrequency under 10 GHz ($\lambda > 3$cm). This frequency band is little affected by the atmosphere. On the other hand, the generation of a very narrow beam requires a very

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[1] Reference used for the DC/DC converter TRL estimate

large radiating surface in which the phase of the signal must be uniform. For the time being, two frequencies have been identified (ISM bands): 2.45 GHz and 5.8 GHz.

- Radiofrequency above 10 GHz. These frequency bands are strongly affected by the atmosphere. The higher the frequency, the larger the atmospheric losses. Thus the availability of the link and its power capacity (losses) will depend on the weather conditions (rain, snow, fog, etc.) at the Ground Power Station. On the other hand, the generation of narrow beams requires a smaller radiating surface. Frequency allocations (ISM) would be possible at 24 GHz, 61 GHz. Technologies to use 122 GHz and 244 GHz are not available.The efficiency of the power generator devices is often poor.

Another option is to use Infrared (0.8µm or 1.5µm). These wavelengths are blocked by the cloud coverage (it's a bit like visible light that is filtered by clouds, which lowers the performance of solar panels on the ground). The link availability of the wireless power transfer is conditioned by cloudiness. The main advantage of this technology is that the beams are extremely narrow (µrad) and therefore the spot on the ground is small (hundreds of meters). The power efficiency of the laser is very poor. Note here the existence of solar pumped laser technology which allows direct conversion of sunlight to laser power.

The chosen frequency (apart from the varying affection from the atmosphere) is constraining the size of the WPT antenna and the collecting area of the GPS too.

The big advantage of the RF under 10 GHz (2.45, 5.8 GHz) is the negligible loss through the atmosphere which allows optimal operation 24/7. On another side, higher frequency (24 GHz) allows smaller WPT antenna diameter and GPS area. The drawback is the higher loss of the atmosphere depending on the weather.

2.3.2 Environmental, health, safety, and security factors

The following environmental, health, safety and security factors have been identified:

- Factors that may prevent environmental constraints are:
    - Launch – Introduction of propellant by products into the atmosphere, especially into the upper atmosphere where effects are less clear, and also the additional impact of black carbon (soot) and more complex exhaust by products from kerelox and solid systems
    - Local heating from the beam – Energy lost to the atmosphere due to beam absorption will present as additional heating locally. This is dependant on the transmission frequency and should be low if beam efficiency is maximised. Its important to note that all the energy beamed to the ground will eventually be lost to the atmosphere as heat energy anyway through use in electrical systems. This additional heating is the same as for any electrical generation system not based on the direct effects of solar heating on the ground (e.g. Nuclear)
    - Local heating at the GPS site due to efficiency losses
    - Effect on local flora and fauna due to construction of and operation of the GPS – e.g. loss of habitat, effect on behaviour (e.g. birds in the vicinity of the GPS)
- Factors that may effect health and safety
    - Effect of the power beam
    - Physical effect on human activities in the locality of the GPS (not due directly to the beam), e.g. farming under the GPS if on-shore or fishing if off-shore
- Factors that may effect security

- The system will represent critical national infrastructure for the receiving nation, and so may be a target for hostile attacks, hence will need to implement physical and cyber attack mitigation. Physical for the GPS is largely the same as for any ground based power station, but must also be considered for the SPS as well. Cyber security will need to be considered for the system as a whole to prevent hostile take-over, denial of service, or damage.

2.3.3 DC – RF Power Conversion

At this stage, we consider four possible power amplifier technologies: SSPA, TWTA, Magnetrons and Klystrons.

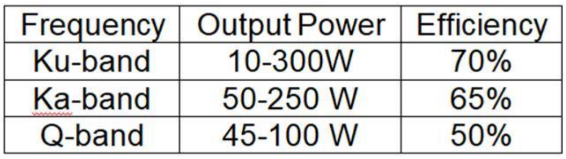
2.3.3.1 TWTA

TWTA (traveling-wave tube amplifier) are RF power generator using vacuum tube/helix/electron beams. They are classically used as power amplifiers for X to Q/V bands (8 to 50GHz) in satellites.

Space qualified TWTA have fair efficiency in high frequency band (Ku, Ka-band) as reported in Table 2-4.

These pieces of equipment have the following drawbacks:

- ✓ high cost because they require sharp tuning and magnetic shielding
- ✓ thermal complex accommodation to evacuate calories from TWTA hot spots (cathode)



Frequency	Output Power	Efficiency
Ku-band	10-300W	70%
Ka-band	50-250 W	65%
Q-band	45-100 W	50%

Table 2-4 Typical state of the art of space TWTA

It is unlikely that major advances in terms of PAE increase will occur in the next 20 years. Research on TWTAs initiated in the 1960s resulted in a PAE exceeding 70% but with fairly complex technological solutions: multiple collectors (up to 5), very high current density anode, very high voltage power supply.

2.3.3.2 Magnetron

The magnetron is a high-power vacuum tube utilized in early radar systems and currently found in microwave ovens and linear particle accelerators. It functions by generating microwaves through the interaction of a stream of electrons with a magnetic field as they move past a series of cavity resonators—small, open cavities within a metal block. The electrons passing by these cavities cause microwaves to oscillate within, akin to a whistle producing a tone when excited by an airflow. The resonant frequency of this arrangement depends on the physical dimensions of the cavities.

Unlike other vacuum tubes, such as klystrons or traveling-wave tubes (TWTs), the magnetron cannot operate alone as an amplifier to increase the intensity of an applied microwave signal, it can, however, be converted into a two-port amplifier. This converted magnetron is capable of delivering over 30 dB of gain while remaining phase-locked to the input signal across a wide frequency range. This transformed use of the magnetron is known as the MDA (Magnetron Directional Amplifier). To further enhance its capabilities, the MDA can be integrated with an inexpensive slotted waveguide array (SWA) antenna, forming the Electronically-Steerable Phased Array.

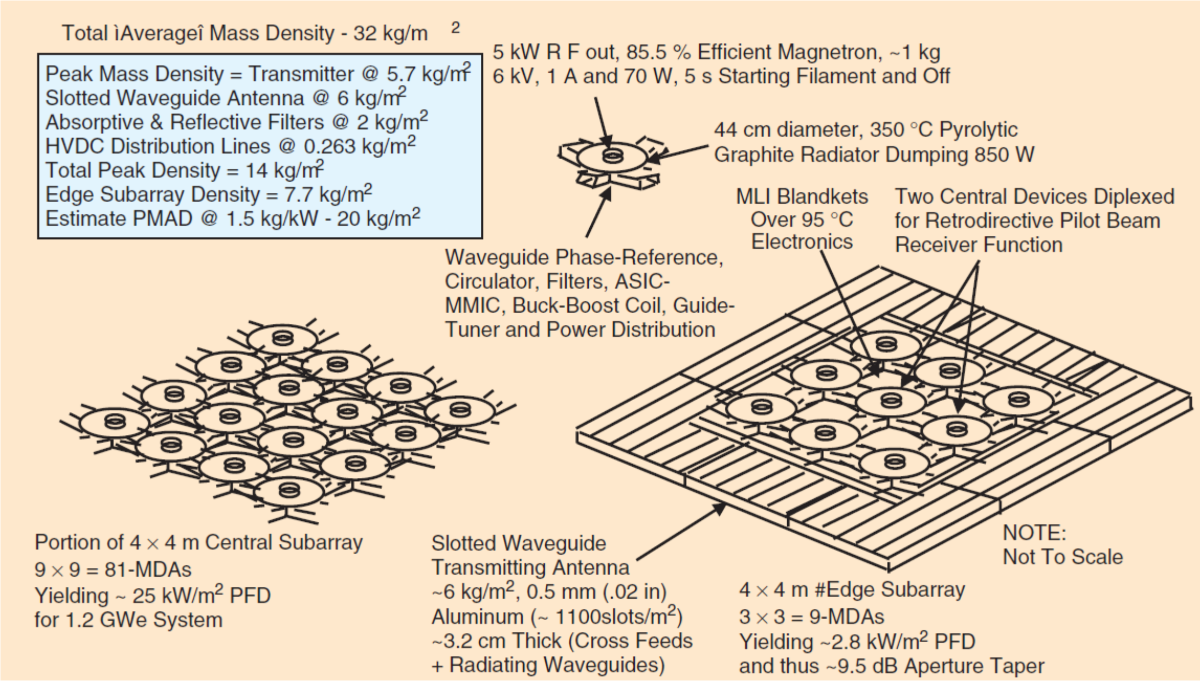


Figure 2-7 MDA example for SBSP possible application (see [RD27])

While presenting weight to power values lower than Klystron technologies this could remain a major problem for the needed power to be converted on board. However this type of DC-RF generation could reach, according to different studies (See [RD28]), efficiencies up to 80-85% in UHF and C-band, while currently settling at slightly lower values.

2.3.3.3 Klystron

By construction, the klystron is the most suitable tube amplifier for delivering high CW power in narrow band from UHF to W-band. CW klystrons have been used for decades in particular to provide RF power to particles accelerators, and to heat the plasma of Tokamaks for nuclear fusion experiments.

In term of power supply, klystrons are usually biased with voltage ranking from 15 kV to 100 kV, depending of the requested output power and frequency range. For example, THALES and others supply klystrons with the following characteristics on the market:

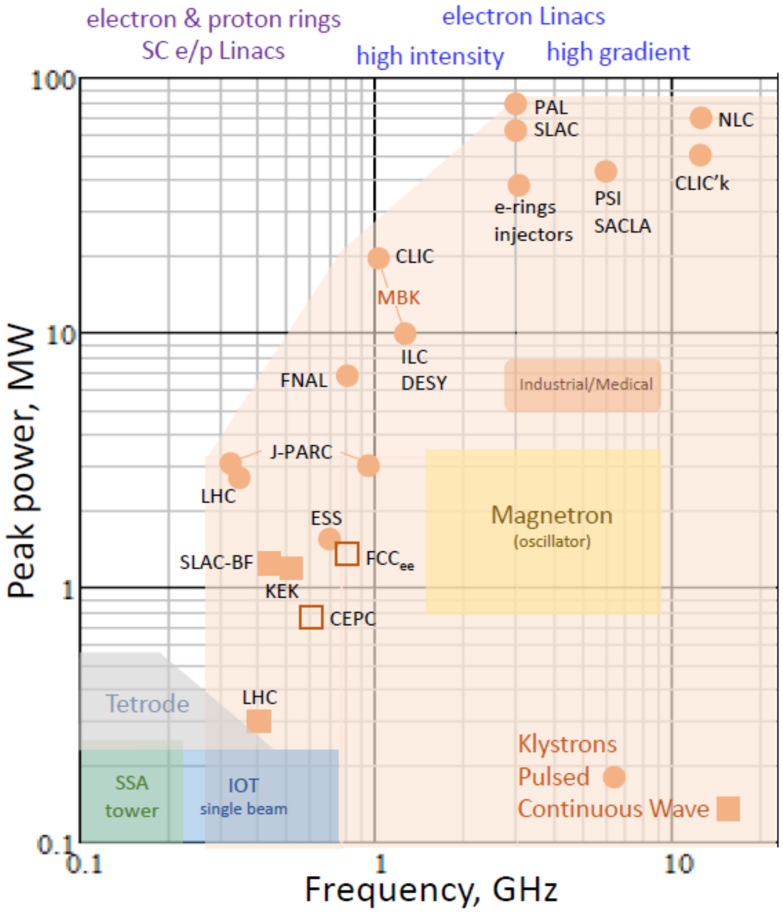


Figure 2-8 Overview of the Klystrons high power technologies (see [RD29])

Today's efficiency of CW klystrons (considering values in between concrete applications at the moment and simulations that have been validated with higher efficiencies) is typically 75% in UHF band, 65% in C-band and 55% in X-Band. This efficiency could be improved by decreasing the perveance of the gun (voltage divided by current at the power three half).

Usually klystrons have a perveance between 0.25 and 2.0E-6. For example, decreasing the perveance up to 0.5E-6 could allow even higher efficiencies. The drawback is a higher acceleration voltage, with a negative impact on the weight.

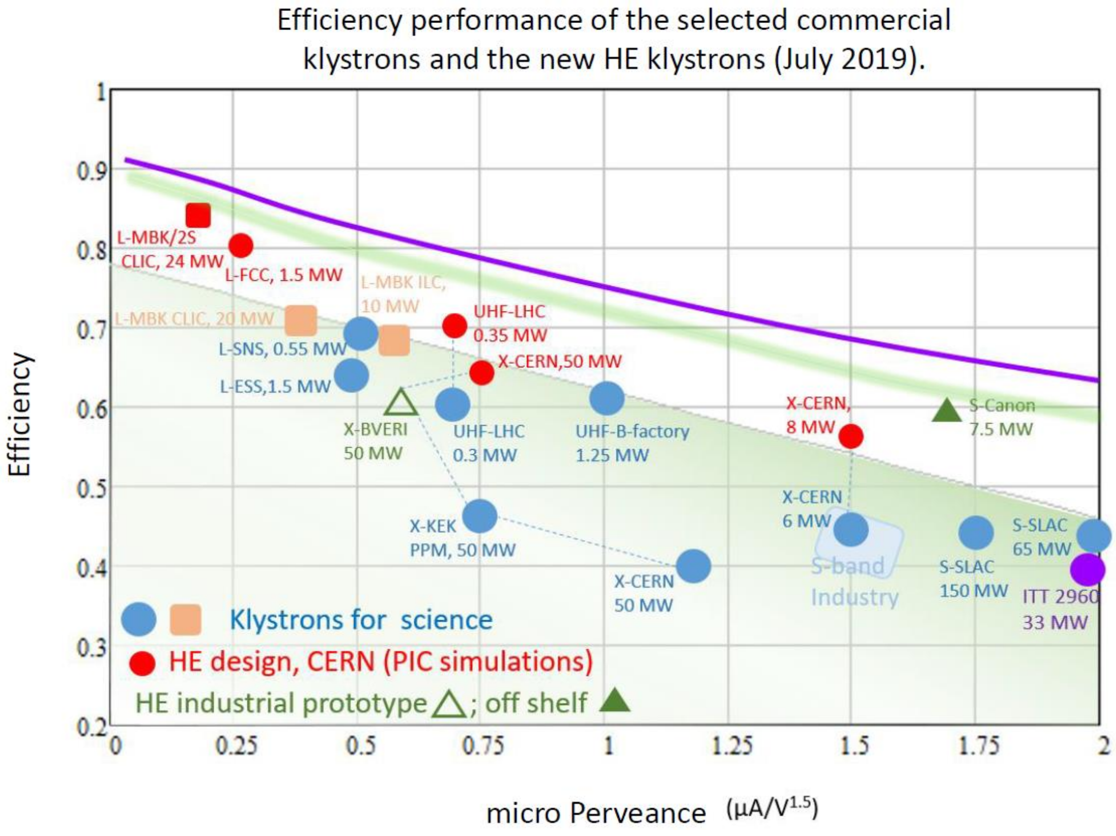


Figure 2-9 Efficiency state of art for Klystrons (see [RD29])

As a general rule, in a tube, most of the dissipated power is localized in the collector. Even with 80% power efficiency, there are still kWs of heat to be dissipated for each klystron. On terrestrial systems, technologies such as biphasic cooling allow to evacuate up to 500W/cm². In space, the problem is more to spread the dissipated power on a large surface to be afterwards radiated in space.

The demonstrated lifetime for space TWT is beyond 15 years and successful results have been shown up to 20 years according to a specific technology of the cathodes. The same cathode technology and beam loading can be used in klystrons, so lifetime beyond 20 years could reasonably be expected (25 years seems a reasonable projected lifetime for this technology).

A drawback of klystrons is the mass. Typical mass of tubes using permanent magnets focusing is in the range of 3 kg/kW of RF power. The other contributor to the mass is the power supply. Today, for space application, the power to mass ratio is about 5 kg/kVA of delivered power to the tube. Therefore, today the mass of a Klystron seems to be a more limiting factor than the achievable efficiency. However, there is still room for optimization of this parameter.

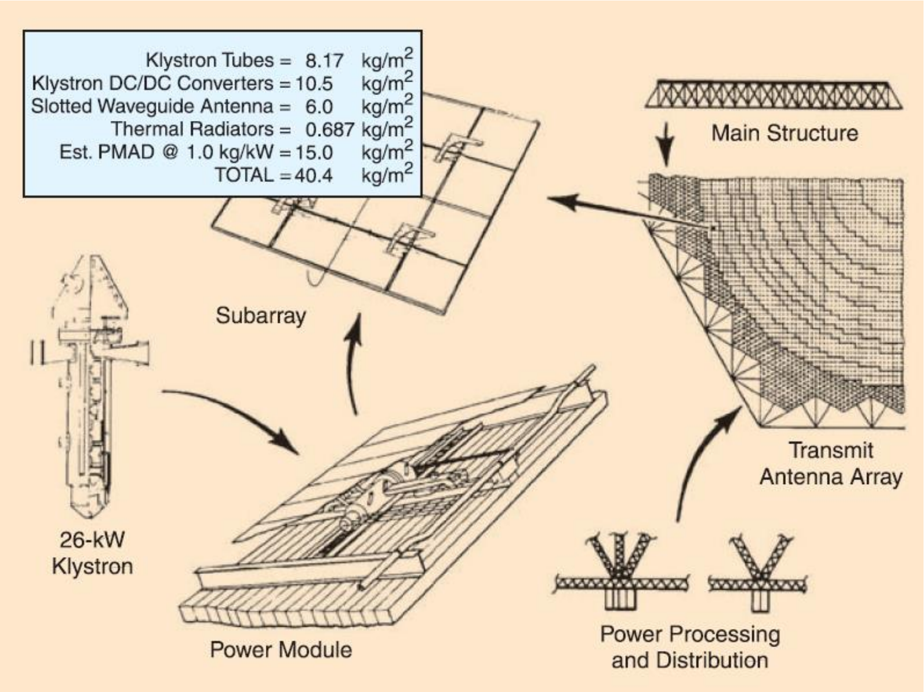


Figure 2-10 Possible example of Klystron integration for a SBSP application (see [RD27])

2.3.3.4 SSPA

Unlike the slotted waveguide array where a tube would feed many radiating slots, the solid-state transmitter places a 5.8 GHz power amplifier and phase shifter behind every radiating element. Because a phase shifter is located at every element, the advantage of this approach over the tube transmitters is the elimination of grating lobes when electronically steering the beam. However, microwave filters are needed on each element to suppress both close-in carrier noise and harmonics generated by the power amplifier.

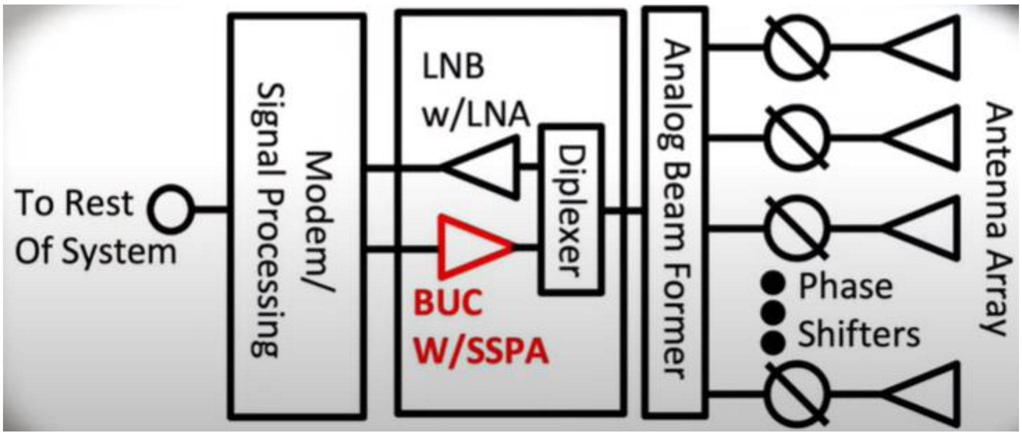


Figure 2-11 Scheme of a SSPA use for phased array antenna

The most suitable device for power amplification in this application is a GaN-based alloy due to its wide bandgap properties. This device allows for high voltage operation, reducing the impact of low-voltage dc-dc converters that affected previous WPT studies based on GaAs devices. With its high breakdown voltage, it enables high power densities and junction temperatures, making it ideal for a WPT transmitter. Predictions on efficiency also indicate that GaN is a perfect fit for this application. The predicted power-added efficiency (PAE) comparisons of GaN to InGaAs and SiC with harmonic tuning is shown in Figure 2-12.

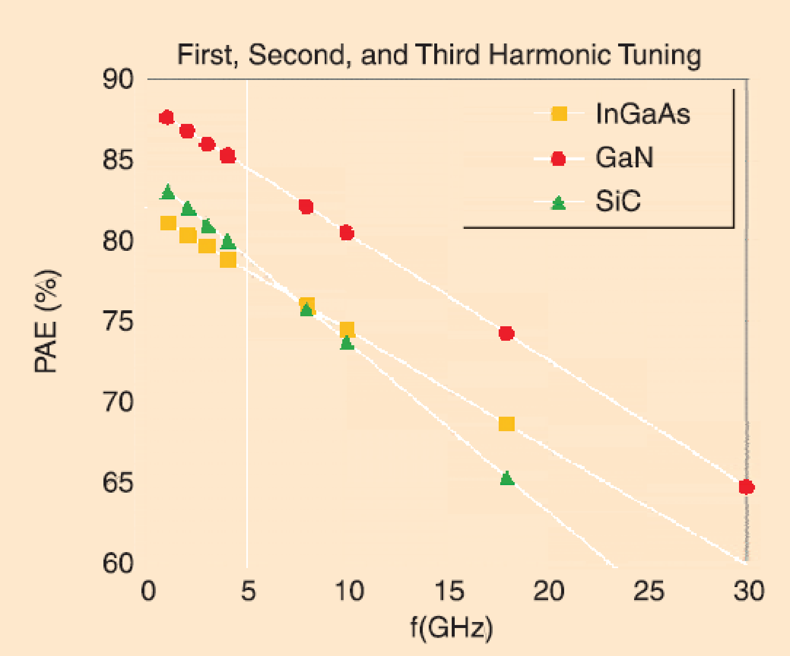


Figure 2-12 Predicted solid-state device PAE performances (see [RD27])

It shall be noted that existing SSPA are typically used in Class A or AB (which present lower efficiencies of 50-60%) for a better linearity which is not required in the SBSP application. For SBSP, the SSPA shall work in continuous mode, single tone and in nonlinear mode (for example, single unitary amplifier operating in Class E)

In recent developments, Class E solid-state power amplifier designs have shown excellent results in the microwave frequency range as reported in Table 2-4.

Frequency (GHz)	Output RF Power (W)	Drain Efficiency/PAE
2.45	1.27	- /72%
5	0.61	81%/72%
8.35	1.41	64%/48%
10	0.10	74%/62%

Table 2-5 State-of-the-art microwave Class E power added efficiencies (see [RD27])

While Class E amplifiers can theoretically achieve 100% efficiency, they operate in a highly nonlinear manner, leading to the generation of unwanted harmonics that necessitate RF filtering in the transmitter. To attain the required efficiencies for an SPS transmitter, the output of a GaN power amplifier can be combined with either an harmonically tuned circuit (Class F) or operate as a switch (Class E). A contract was awarded in the SERT program to investigate AlGaN heterojunction field-effect transistors (HFETs) on SiC substrates operating in Class E.

Using existing AlGaN HFETs in a Class E circuit, simulations have shown they are capable of achieving PAEs approximately of 70% at 5.8 GHz, but higher values could be expected with further research and development.

2.3.3.5 Other technologies

A solar-pumped laser (or solar-powered laser) is a laser that shares the same optical properties as conventional lasers such as emitting a beam consisting of coherent electromagnetic radiation which can reach high power, but which uses solar radiation for pumping the lasing medium. This type of laser is unique from other types in that it does not require any artificial energy source

Figure 2-13 The Nd:YAG solar-pumped laser system with a 0.9 m diameter Fresnel lens and a laser head positioned in its focal zone.[“Highly efficient solar-pumped Nd:YAG laser” Dawei Liang,* and Joana Almeida]

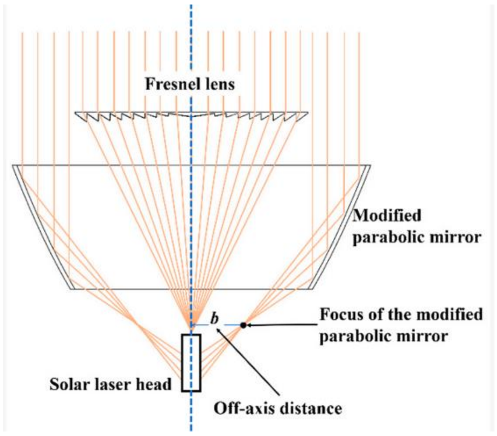
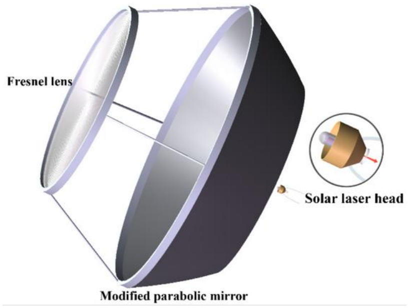


Figure 2-14 “Highly Efficient Solar Laser Pumping Using a Solar Concentrator Combining a Fresnel Lens and Modified Parabolic Mirror”, Zitao Cai & al.



2.3.4 Antenna

The main physical characteristics for the antenna are its type or geometry (planar phase array, parabolic solid reflector, square aperture, circular aperture) and its physical area (diameter or sides).

The antenna is characterized by many parameters and efficiency factors. The main ones are:

- *Half Power Beam Width (HPBW)*: is the angular range of the antenna pattern in which at least half of the maximum power is radiated. This parameter is important for telecommunication antennas but is of little interest in our case of wireless power transfer.
- *First Null Beam Width (FNBW)*: is the angular separation between the first nulls of the radiation pattern on either side of the main beam. This parameter is very important in our case of wireless power transfer. It allows calculating the surface of the Ground Power Station which is necessary to intercept the entire power beam (main beam).
- *Beam efficiency:* is the ratio of the power radiated within the main beam to the total power radiated. It allows computing the power contained in the main beam and estimating the power radiated outside the power beam.

A critical operational characteristic will be the pointing capability of the power beam and the pointing accuracy of that beam. Beam aiming capability and accuracy depends on the mechanical system of the antenna and on the generation of the relevant illumination law.

In order to manage GW-scale WPT, the most challenging issues are linked to the antenna dimensions of hundreds (to thousands) of meters. For these range of dimension and considering current launcher fairing limitations, the use of in-orbit assembly and/or manufacturing is required.

Moreover, many aspects concerning these antennas must be studied and be the subject of technological development:

- **Antenna Design**: the huge Antenna structures and widely distributed electronics drives to the use of innovative technologies that have to be explored for this futuristic application. For example, a well-known constraint of array antennas is the proper phase alignment between elements.
- **Antenna Construction and Commissioning**: an important issue is the in-orbit Antenna Integration and Testing, which requires special installation methods. Moreover, in order to ensure the Antenna planar radiative surface i.e. the mechanical and electrical alignments between Antenna Sub-Assemblies, dedicated measurement techniques.
- **Antenna Maintenance**: Antenna design has to take in to account the ergonomic needs for the commissioning phase, with modular architecture, that is suitable also for the maintenance strategies, in terms of failure Detection/Isolation and of repair activities. In particular, in case of presence of alignment mechanisms, those should be regularly checked to ensure the good pointing of the beam.
- **Antenna Costs**: Various approaches could be developed to reduce antenna costs. In the case of flat panel antennas, a high integration of the electronic and RF circuitry would allow a lower cost considering a high volume of production. Moreover, it would improve overall mass and volume. In case of reflector antenna, in-orbit assembly or in-orbit manufacturing will reduce the need for advanced deployment mechanisms. Advanced reflector material should also be studied since flexible, light, grid-like material could reduce antenna mass and cost.
- **Antenna Performances**: In order to increase the phased array antenna efficiency, a low coupling between radiated elements shall be achieved. There are various technics to

reduce the coupling, such as the use of metamaterials.

2.3.5 Antenna technical review

There are several categories of SBSP microwaved beamed concepts, as described in the following sections.

2.3.5.1 Central antenna with classical solar panels

This configuration could be considered as a scale-up of a classical satellite. The solar panels rotate around an axis to keep pointing Sun. The main drawback of this solution is the need of long high power cables going from solar panels to the antenna. However, this concept might not require very high efficiency solar cells and could be scalable by taking this constraint in the development. Current Chinese MR-SPS concept () is in this category.

Figure 2-15 Chinese MR-SPS concept

2.3.5.2 Light Reflectors toward a central sun to DC to RF converter

This configuration is of interest as it removes the need of long and high power distribution cables. At a first sight, the structure mass might be higher and high efficiency cells might be mandatory for the Sun to DC conversion. SPS Alpha illustrates this concept (Figure 2-16).

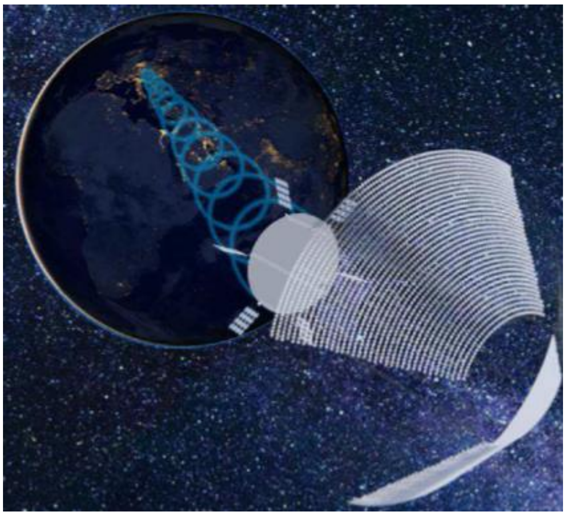


Figure 2-16 SPS Alpha concept

2.3.5.3 Helical antenna concept

The Helical antenna concept is supported by the UK Space Energy Initiative. The main advantage is that it does not require any rotation mechanism after deployment. Some drawback might still come from the antenna that has a variable aperture as seen from ground. This leads to a variable diffraction pattern that might be difficult to manage in some orientations.

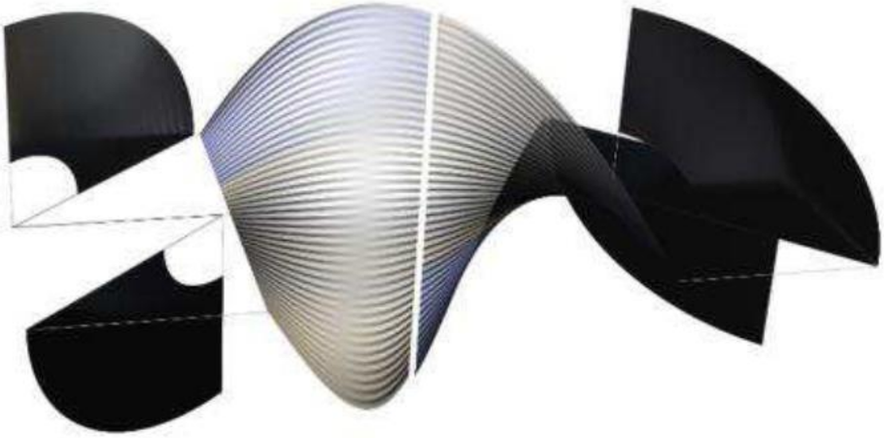
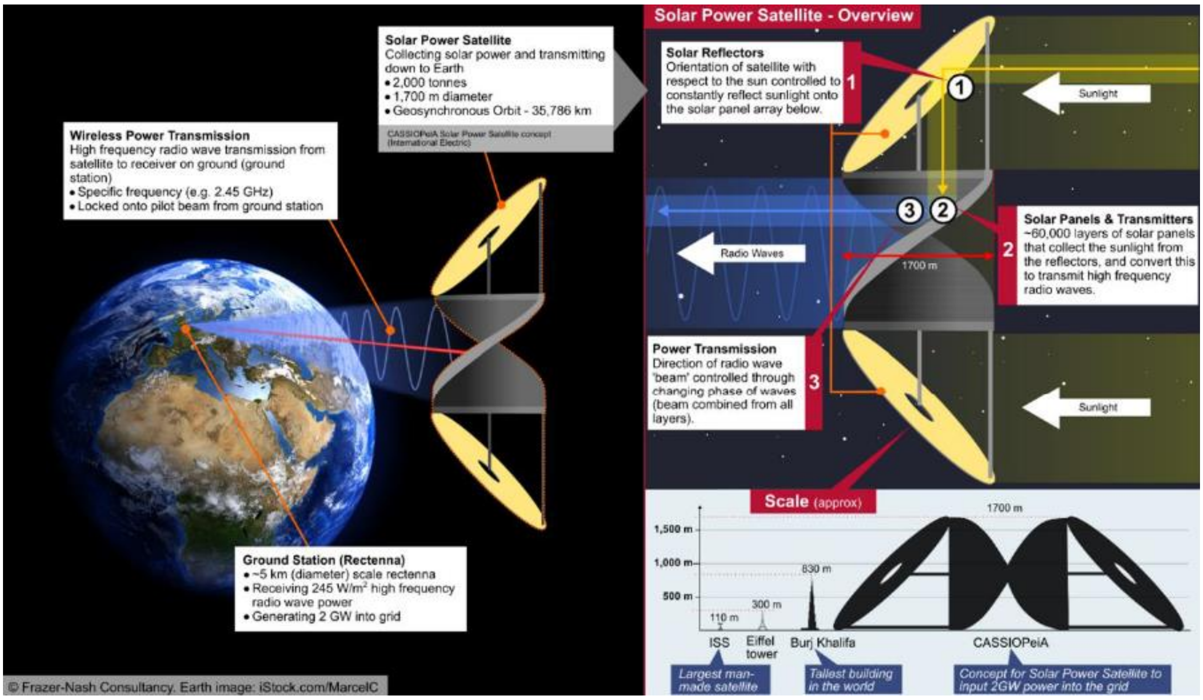


Figure 2-17 Cassiopeia concept



Solar Power Satellite
Collecting solar power and transmitting down to Earth
- 2,000 tonnes
- 1,700 m diameter
- Geosynchronous Orbit - 35,786 km

CASSIOPeiA Solar Power Satellite concept (International Electric)

Wireless Power Transmission
High frequency radio wave transmission from satellite to receiver on ground (ground station)
- Specific frequency (e.g. 2.45 GHz)
- Locked onto pilot beam from ground station

Ground Station (Rectenna)
- ~5 km (diameter) scale rectenna
- Receiving 245 W/m² high frequency radio wave power
- Generating 2 GW into grid

© Frazer-Nash Consultancy. Earth image: iStock.com/MarcelC

Solar Power Satellite - Overview

1 **Solar Reflectors**
Orientation of satellite with respect to the sun controlled to constantly reflect sunlight onto the solar panel array below.

2 **Solar Panels & Transmitters**
~60,000 layers of solar panels that collect the sunlight from the reflectors, and convert this to transmit high frequency radio waves.

3 **Power Transmission**
Direction of radio wave 'beam' controlled through changing phase of waves (beam combined from all layers).

Figure 2-18 Concept « CASSIOPeiA SPS » - Crédit : Frazer-Nash Consultancy, 2021

2.3.5.4 Thin film rotating plan

In this concept, the solar array and the antenna are built on the same film with almost transparent electronics to allow power generation independently of the side illuminated by the Sun. The advantage of this concept is the possibly very simple deployment. However, as the antenna needs to be pointed toward Earth and the panels towards the Sun, a rotation is imposed on the satellite. This leads to lower levels of power delivered on parts of the orbit. The concept is currently developed by Caltech.

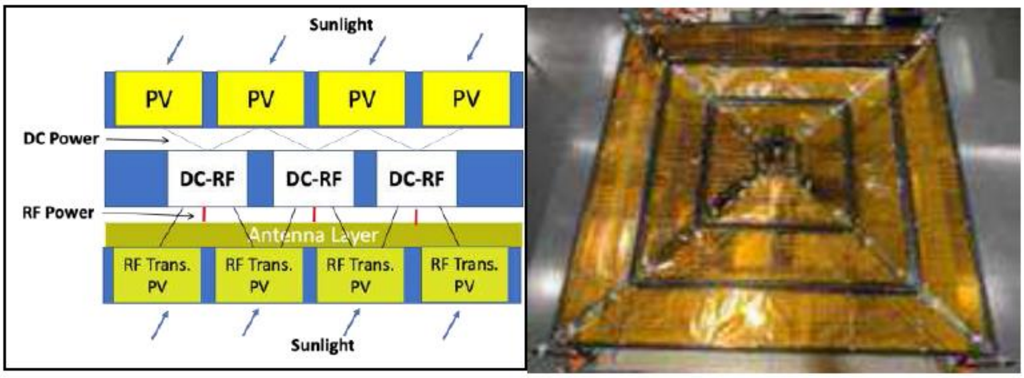
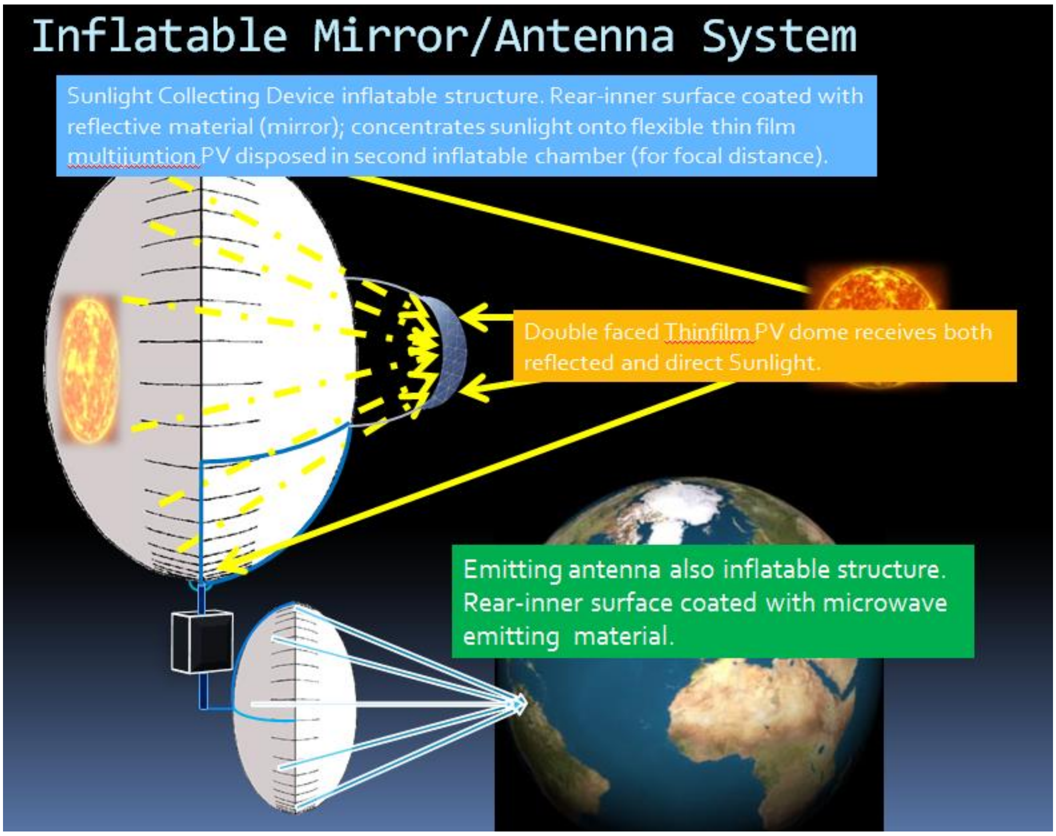


Figure 2-19 Caltech thin-film concept

2.3.5.5 Inflatable parabolic antenna



Inflatable Mirror/Antenna System

Sunlight Collecting Device inflatable structure. Rear-inner surface coated with reflective material (mirror); concentrates sunlight onto flexible thin film multiijuntion PV disposed in second inflatable chamber (for focal distance).

Double faced Thinfilm PV dome receives both reflected and direct Sunlight.

Emitting antenna also inflatable structure. Rear-inner surface coated with microwave emitting material.

Figure 2-20 Inflatable parabolic antenna

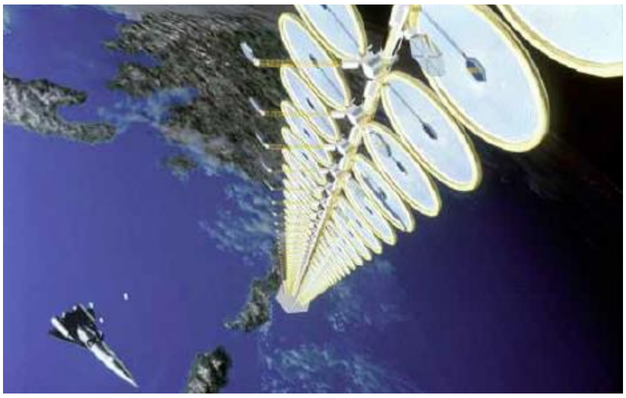


Figure 2-21 NASA's Solar Tower is based on inflatable devices

2.4 Propagation through the atmosphere

We are interested only in the effects of the atmosphere on the radio waves which cause an attenuation of the signal strength (loss of power). There are two types of atmospheric effects: effects causing permanent loss (not depending on weather conditions) and effects causing random loss depending on weather conditions above the Ground Power Station:

- ✓ Gaseous absorption is due to gas molecular absorption bands (mainly water vapour H_2O and oxygen O_3) and it causes permanent loss of power.
- ✓ Attenuation by precipitation and clouds depends mainly on frequency, elevation angle, altitude and on the statistical occurrence and intensity of clouds and rain showers at the GPS location.

The atmosphere may have an additional effect on the transmitted RF power: depolarization. Depolarization of RF signal is caused by the anisotropy of the propagation medium due for example to the oblateness of raindrops and non-spherical crystal ice. If the RF signal emitted by the WPT antenna is depolarized (a circular polarization becomes elliptical), then the polarization matching of the rectenna could be not perfect, leading to some loss. At frequency lower than 10 GHz, this effect is negligible.

2.5 Ground power reception, management, and distribution

After capturing a large amount of sunlight through photovoltaic cells and converting it into radiofrequency waves, they are then transmitted to ground based station, i.e. to a rectifying antenna array on earth which can be considered, under adequate assumptions, as an AC wave generator. The power obtained from the RF antenna needs to be firstly straightened and then converted back into AC before hooking it to the distribution network. Due to the high frequencies involved, a suitable power signal management is necessary in order to properly transfer it to the network.

The main functional blocks acting on the distribution and conversion of the ground power distribution and management system are summarized in Figure 2-22.

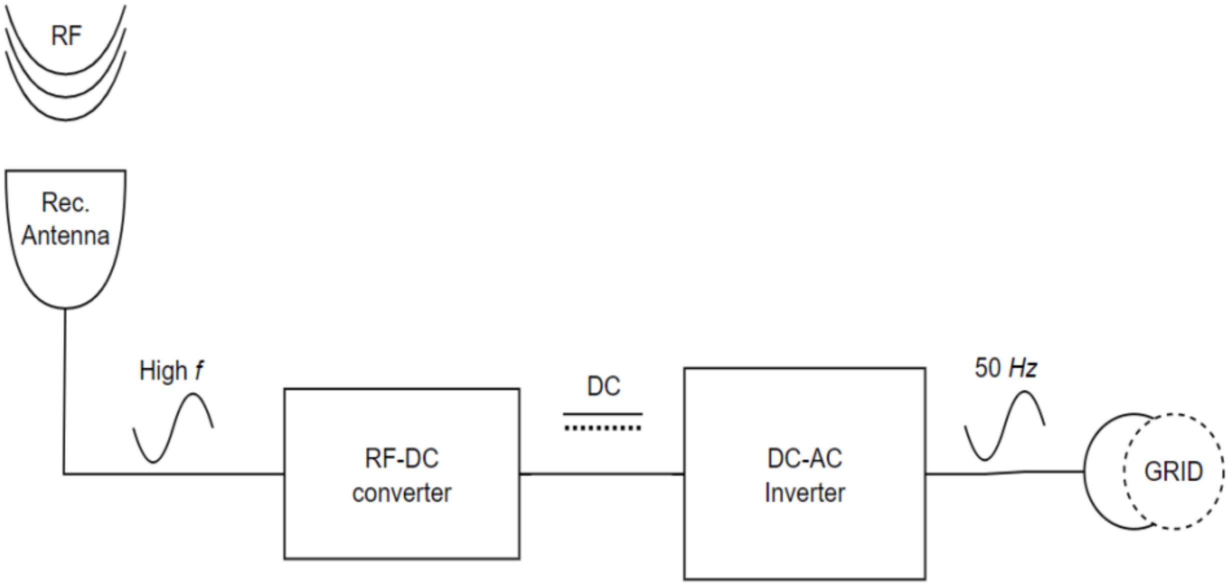


Figure 2-22 Ground power distribution and management schematic

The network system features the following distribution characteristics [According to the European standard EN 50160]:

- LV (Low Voltage): the grids that have voltages below 1kV
- MV (Medium Voltage): voltages between 1kV and 35kV
- HV (High Voltage): grids that have voltages above 35kV

These represent the vast majority of distribution networks in Europe with a frequency (imposed at the European level) of 50 Hz.

2.5.1 RF-DC converter or rectenna

The rectifier allows managing the alternating component of the RF signal to convert it into DC signal (the RF-DC converter). Given the frequency involved, the rectifiers needs to be developed to improve their performances in terms of mass saving and efficiencies as high as possible. The efficiency is affected by the input power from the receiving antenna and the type of converter used. Considering the different converter technologies, the efficiency can vary in the range 20%-80%. Furthermore, ultrafast diodes with different construction characteristics with respect to the common Si ones are implemented to allow efficiency improvement. Among the types of materials used, those with GaN show the best performances, representing the current state of the art. The efficiencies obtained are also a function of the RF frequency used for transmission [RD26].

A rectenna (rectifying antenna) is a special type of receiving antenna that is used for converting electromagnetic energy (RF) into direct current (DC) electricity within wireless power transmission systems. The efficiency for the purposed application varies to 60% up to 85/90% depending on the operative frequency (and the incident power density too).

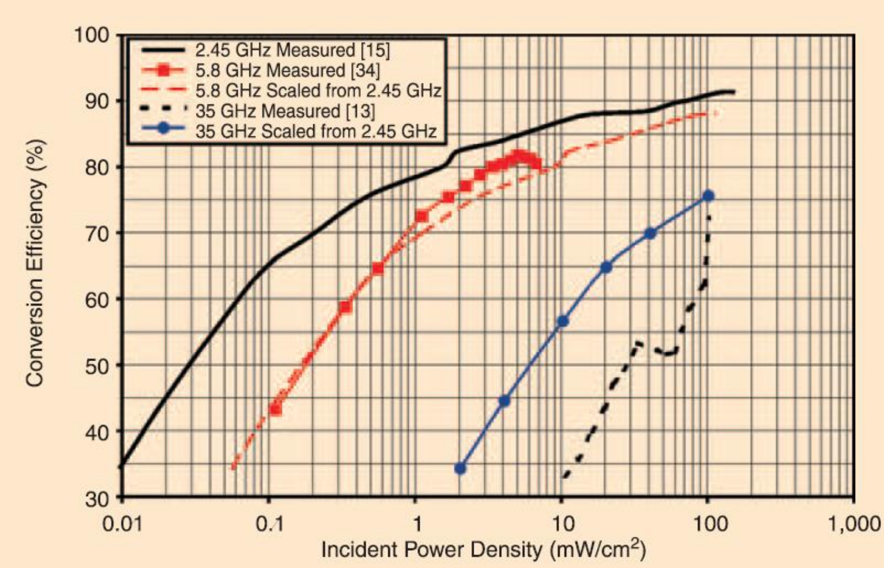
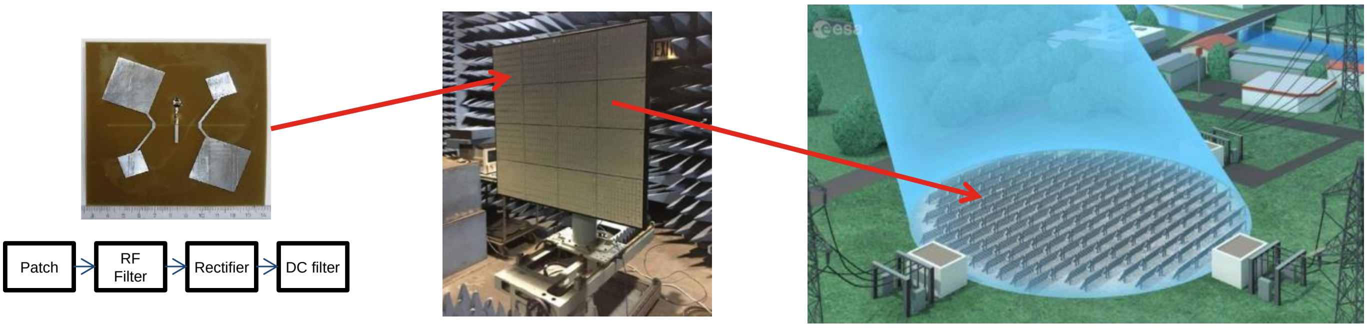


Figure 2-23 State of art of rectenna efficiencies (see [RD27])

For SBSP applications large rectenna panels or meshes are used for the GPS. Each rectenna panel (or mesh section) includes an array of tiny rectenna receiving element (RE). A RE includes a patch and a rectifier.



Patch (RE) **Panel** **Ground Power Station**

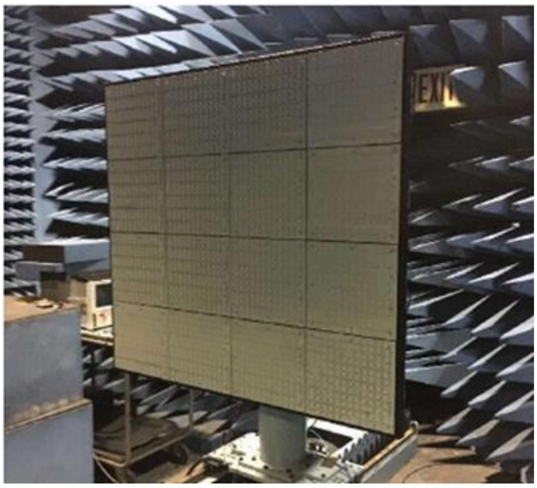


Figure 2-24 Scalable, High-Sensitivity X-Band Rectenna Array for the Demonstration of Space-to-Earth Power Beaming, (see [RD30])

Figure 2-25 Rectenna meshes (credits : FT.com)

2.5.2 DC-AC converter

The next power stage is focused on the regulation of the DC part and its conversion into AC (inverter function). This process imposes an evident architectural limit, i.e. the maximum voltage of the DC part and the maximum conversion power. Actually, the converters topology, considering the construction constraints and the materials, are able to work with voltages of around 1-5 kV (see RD[20] RD[21]), at the same time the current state of the art shows that the maximum conversion powers are around 1-7 MVA.

It is shown from the catalog that there are possible solutions able to provide a wide range of AC output voltages ranging up to 40 kV_{AC} (see RD[22]). This type of system builders are already in the current market. Thus TRL of such architecture is considered very high (TRL 9) and various future improvements may increase the range of operability in power and input/output voltage.

The various possible configurations are already widely used in the energy sector, just think of all the applications in which there is a large photovoltaic system. In this context, the analyzed system could be set up modularly (given the possible power ranges) in relation to the types of converters currently available.

2.5.3 Ground power management characteristics

The main characteristics of the RF-DC and DC-AC converters are summarized in the table below. Possible expected future improvements of converters performances are also listed in comparison to the previous ones.

	State of the Art	Future feature

RF-DC converter (Rectifier)	Efficiency		20-80 %	20-80 %
	Equivalent TRL ground Level		4	9 (with adequate funding)
	Physical constraint		Packaging and GaN Diode manufacturing	Packaging and GaN Diode manufacturing
	Electrical Constraint		Ultrafast diodes and ad-HOC PCB design	Ultrafast diodes and ad-HOC PCB design
DC-AC converter (Inverter)	Efficiency		99%	99%
	Electrical characteristics	$V_{DC\ in}$	1-5 kV	Up to 15kV
		$V_{AC\ aout\ rms}$	Up to 40 kV (in accordance with the GRID standard)	Up to 40 kV (in accordance with the GRID standard)
		Pout	Up to 7.2 MW (for signel inverter)	Up to 7.2 MW (for signel inverter)
	Equivalent TRL ground Level		9	9

Table 2-6 DC-AC converter (inverter) characteristics

2.5.4 Layout of the rectenna in the GPS

Considering an SPS in GEO and a circular RF power beam, the footprint of the power beam is elliptical with a ratio between the minor axis (b) and the major axis (a) equal to sin(elev[2]). The major axis is aligned with the direction of the SPS.

We assume that the entire footprint of the main power beam (FNBW) is contained inside the area of the Ground Power Station. The minor axis of the footprint is equal to the diameter (D_{RX}) of the power beam on ground.

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[2] *elev* is the elevation angle of the rectenna antenna pointing the SPS

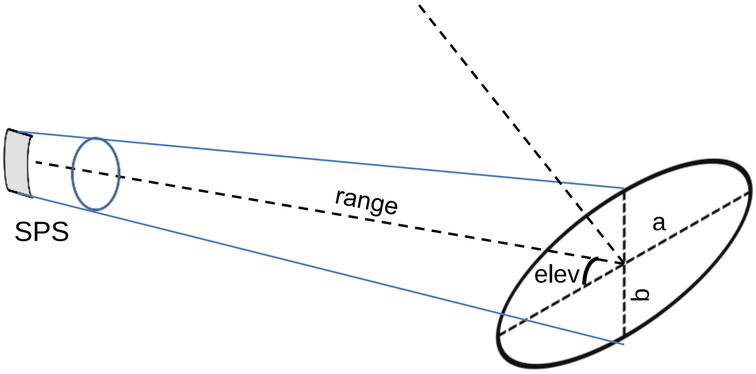


Figure 2-26 Power beam geometric configuration

For the overall GPS layout, there are two options:

- Array of Rectenna panels (printed): this option presents panels shadowing issues with an impact on the floor occupation efficiency.

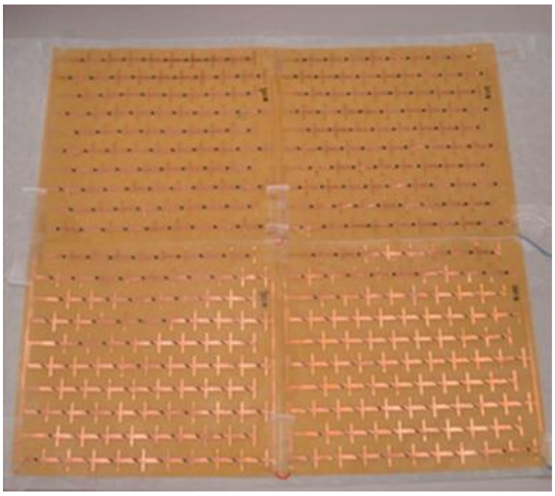


Figure 2-27 Rectenna panel example

- Big rectenna meshes: this option have advantages for atmospheric conditions such as rain and wind allowing also to perform activities under the mesh (e.g., crops) with respect to physical printed panels and higher floor occupation efficiencies too. For rectenna meshes the following configuration are possible:

  - ✓ a single large flat mesh (to receive power from different SPS on different orbits this could be the best solution)

Figure 2-28 Concept of a flat single mesh for GPS layout (credits: INAF)

- ✓ a series of tilted mesh panels of rectennas (better option to receive power only from one SPS in GEO): the angle of the mesh panels should correspond to the angle of the GPS latitude).

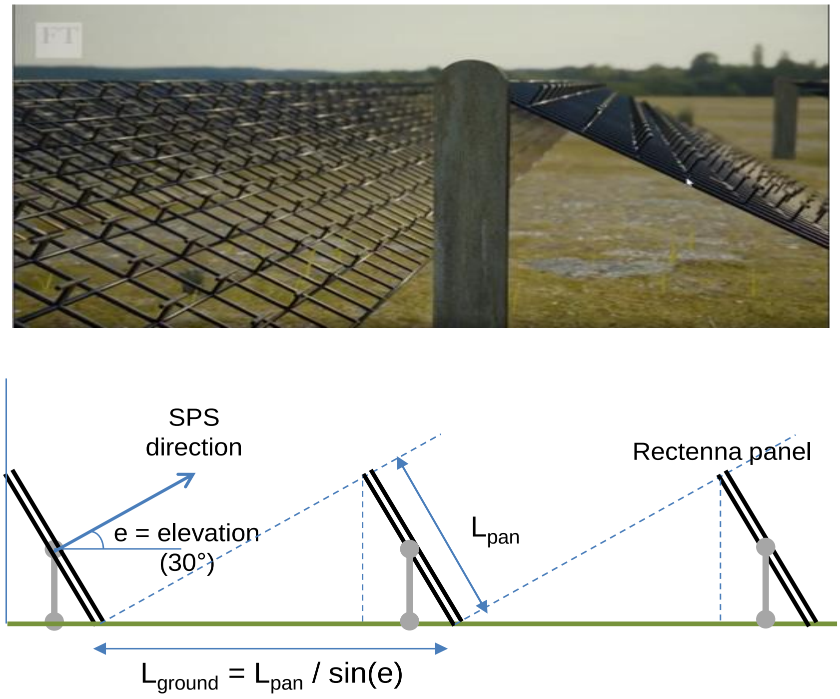


Figure 2-29 Mesh tilted panels concept (credits : FT.com)

2.6 Space assembly, maintenance, and servicing

SBSP system will make use of in-orbit servicing and assembly, an emerging field within the aerospace industry that involves the use of robotic technology to perform various tasks in space, such as repairing and maintaining satellites, assembling new structures, and manufacturing materials. This technology has the potential to revolutionize the way we operate in space, making it more cost-effective and efficient. One of the key challenges in the development of In-orbit servicing is the need for advanced robotics technology that can operate effectively in the harsh environment of space. This requires the development of new hardware and software systems that can withstand the extreme temperatures, radiation, and vacuum conditions of space. In recent years, significant progress has been made in this area, with several companies and research organizations working on the development of these technology.

There are several in-orbit servicing projects and missions currently under development or announced by industrial or institutional actors and, at the moment, it seems that the majority of IOS missions are still launched or funded by public actors. Most European start-ups which are active in the IOS market and have scheduled a launch in the coming months/years are mostly funded publicly. Life extension, Refuelling and Active Debris Removal (ADR) seem to be the most advanced and promising applications with several missions scheduled to launch in the next couple of years.

Currently, three players have launched their servicers: Northrop Grumman (SpaceLogistics), Astroscale and D-Orbit.

- SpaceLogistics launched *its* first servicer (MEV-1) in 2019 to provide Life Extension services and, in April 2021, it has successfully completed the docking of their second servicer, Mission Extension Vehicle-2 (MEV-2), to the Intelsat 10-02 commercial communications satellite, which was running low on fuel after being in orbit since 2004.
- Astroscale, on March 2021 *launched* ELSA-d, with its servicer designed to safely remove debris from orbit that has completed the demonstration phase and successfully tested the ability of its end-of-life servicer to capture the client spacecraft using the ELSA-d's magnetic capture system.
- D-Orbit launched its *In*-Orbit Now (ION) Satellite Carrier in September 2020 and deployed the first 12 Planet SuperDoves. In May 2021, D-Orbit demonstrated this commercial last-mile delivery service, deploying 20 satellites during its second mission and performed manoeuvres, proving it could change its altitude and inclination.

Thales Alenia Space Italia is actively working in two consortia targeting IOS demonstration before 2030.

There are several technological challenges in the development of a reliable IOS product, and for this reason technological development are undergoing both at system and technological level. The most important to be cited are:

H2020 (EU Funded):

- *Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (**SIROM**)*: The main objective of SIROM was to develop a standard interconnect allowing coupling (electrically, mechanically and thermally) of payload to manipulators and payload to other payload. The first version of SIROM interconnect specification has been produced in the frame of the H2020 Call 2016. An updated specification is being produced in the frame of call 2018.

- *MOdular Spacecraft Assembly and Reconfiguration* (***MOSAR***): MOSAR aims at the development of novel, European technologies that would allow standardizing satellites components, facilitating their assembly, reducing time between customer's orders and commissioning in space, repairing and upgrading components directly in orbit instead of replacing entirely a deprecated or damaged satellite. The MOSAR activity focusses on the technology of modules and also prepares a low-cost robot system for demonstration. Additionally, MOSAR is further developing a Standard Interconnect (alternative to the SIROM) named **HOTDOCK**.

ESA projects:

- *Multi-arm Installation Robot for Readying ORUS and Reflectors* (***MIRROR***): MIRROR is a multi-arm robot system meant to assemble optical reflectors for space telescopes, made of individual hexagonal tiles. MIRROR can relocate over a spacecraft, deploying ORUs or reflector segments from their stowed location to their operational location. The overarching objective is to resolve technology issues pertaining to: structure and kinematics of the system, electrical and data architecture, sensoring of the system, implementation of suitable control, operations and operating modes, FDIR.
- *In-Space Assembly and Construction technologies* (***ISAAC***): The objective of this activity is to develop technologies for in orbit assembly of large orbital platforms made of in-orbit manufactured structural elements and modules, components and harness uploaded from ground.

Overall the necessary robotics technologies are being subject of a significant boost nowadays thanks to the IOS demo mission race and parallel technological program run at ESA and EU.

2.7 Structures and materials

Considering the existing SBSP concepts common structure typologies and materials could be exploited for all of them.

The MiraSolar concept is not mentioned due to the fact that this solution to be dropped in an energy cooperative geopolitical scenario because it needs from 40 to 60 solar farms disposed in all continents at several latitude and longitude and across countries that nowadays have antagonist behaviors.

SPS-Alpha (Solar Power Satellite by means of Arbitrarily Large Phased Array)

The overcoming of launchable volumes by current and future launch systems, definitely requires for arbitrarily large systems like the envisaged SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array), the matching of deployable systems with in-orbit assembly in order to maximize the exploitation of the launch capability while minimizing the in-orbit assembly effort and the number of robots although assuming that the robots are of the same order of size as the modules that are handling and will travel over the structure they are building.
As a matter of fact for both the Solar Reflector Assembly (SRA) and the Primary Array Assembly (P, monolithic systems or even simply deployable systems, without a synergic approach given by

deployment plus in-orbit assembly, could never reach arbitrarily dimensions and could therefore only act as technology demonstrators. The SPS-ALPHA, could be based on the similarity with the concept adopted for the JWT (James Webb Telescope), in which a monolithic set of HexBus and a deployable set of HexBus to fit with the launcher's volume and mass capabilities and fly in folded configuration subsequently joined in-orbit after deployment of each module to other neighboring modules.

Following on the other hand a completely deployment approach means to enhance the number of interconnections that operates, with mechanical actuators, the deployment and the subsequent mechanical linking of almost all the SPS-ALPHA modules to one another.

Figure 2-30 Concept for Reflector Module in-flight (folded) & in-orbit (deployed) Configuration (courtesy of NASA)

The modular approach leading to a very large sunlight-intercepting reflector system, could obtained by the in-orbit assembly of many Deployed Reflector Modules each one composed of HexBus units as represented in the following picture:

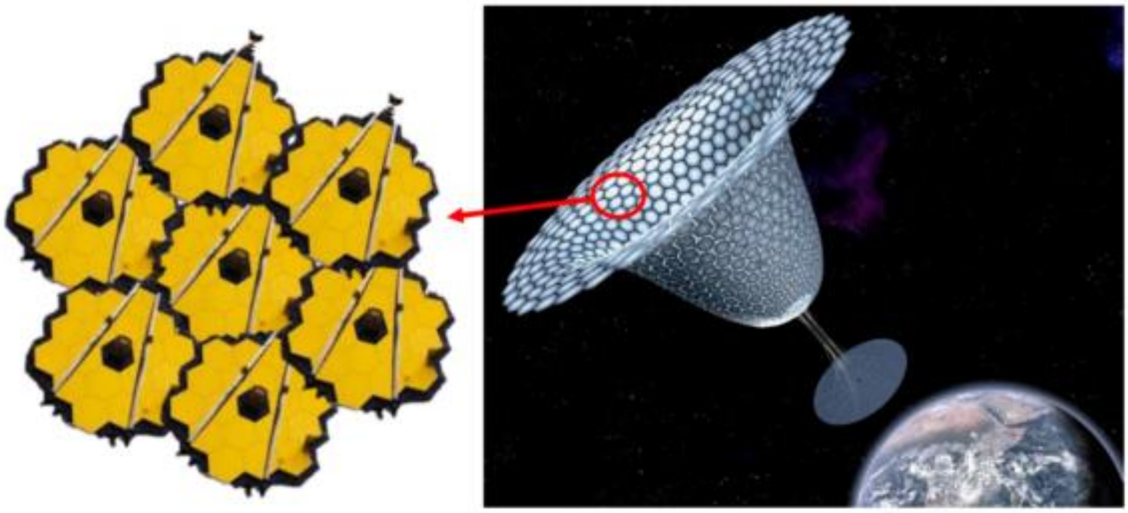


Figure 2-31 Deployed Reflector Modules with Multiple HexBus

Among the SPS-ALPHA the involved technologies will imply the use of lightweight structural components, applied in the various systems and subsystems.

The single HexBus could be hexagonal or could be of different shapes (e.g., triangle, square, or parallelogram) or combinations of shapes (e.g., square and octagon), so long as the combination allows the “tiling” of a plane to create a large aperture system in space.

Despite the final shape it is assumed that the HexBus “Ring Structure “ can be manufactured by CFRP (Composite Fiber Reinforced Polymers) based on carbon fiber unidirectional and fabrics. Depending on the stiffness/strength requirements different fibers can be considered in accordance with TASI spanning from T300J, to M40J and M55J. The manufacturing being based on tubular elements joined by metallic end-fittings to obtain the “Ring Structure “.

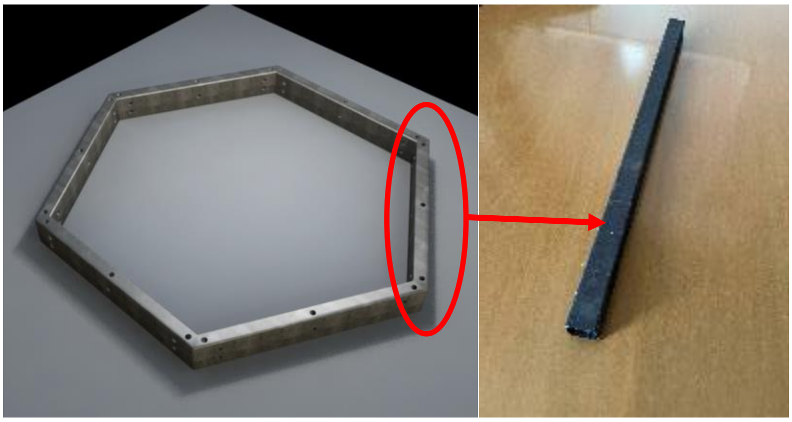


Figure 2-32 HexBus Strut for the “Ring Structure”

The HexBus could be as well based on a sandwich frame design with a big central cut-out and based on CFRP or Al alloy skins and Al alloy honeycomb core.

As a possible alternative the HexBus could be also individually obtained by the deployment of aluminized Kapton® reflector sectors through releasable/deployable or inflatable booms, requiring however a more extensive development effort.

The truss connecting the Primary Array Assembly (PAA) can be based on tubular CFRP elements with metallic end-fittings Solar Reflector Assembly (SRA) as of current design in other space applications.

Figure 2-33 Truss Strut for the "Ring Structure"

CASSIOPeiA

The key concept CASSIOPeiA is based around is its helically arranged omnidirectional microwave antennas, rather than a conventional phased array.

This design is optimized to allow continual Earth and Sun pointing via only an electronic steering of the beam, with no moving elements, i.e. "solid state". Modular – PV and antenna are based from a structural point of view on a repeating sandwich panel design that maximize similarity and minimizes construction costs.

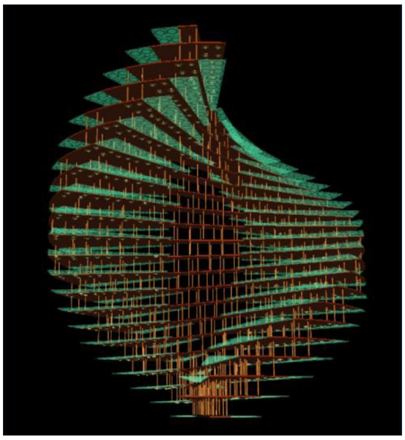


Figure 2-34 CASSIOPeiA Helical Configuration Concept

The sandwich panels can be tuned in terms of honeycomb core height and cells density to provide the necessary strength and stiffness. The skins based on CFRP could are considered to be based on a quasi-isotropic lay-up to provide inserts shear capabilities in all the possible loading directions. The connections of the panels to obtain the helical disposition can be realized with dedicated stand-off connections using CFRP beams as shown in Figure 2-33.

MR-SPS

Multi-Rotary joints SPS (MR-SPS) is a huge Solar Power Satellite located in Geostationary Earth Orbit. Multiple independent solar sub-arrays are used to point to the Sun, continuously and steadily converting solar energy to electric power.

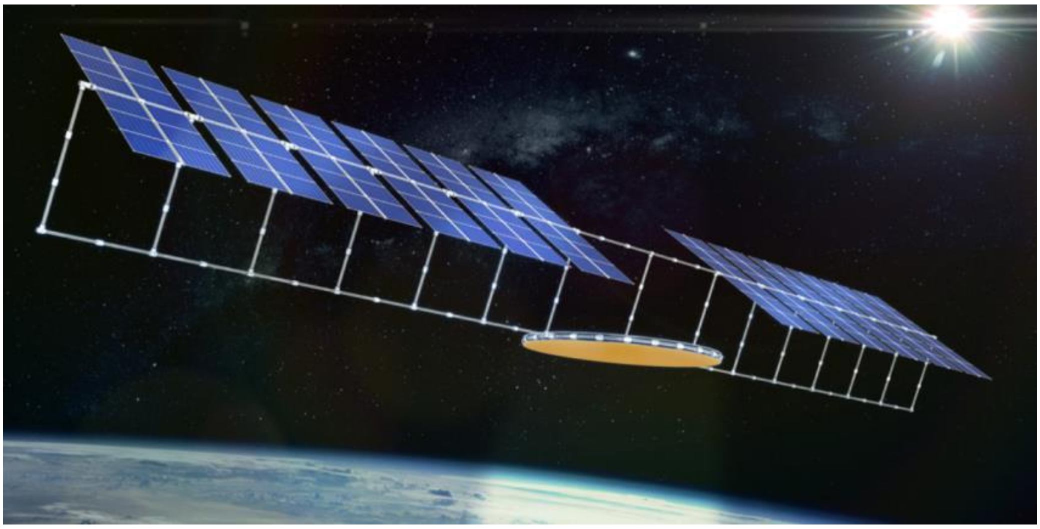


Figure 2-35 MR-SP Configuration Concept

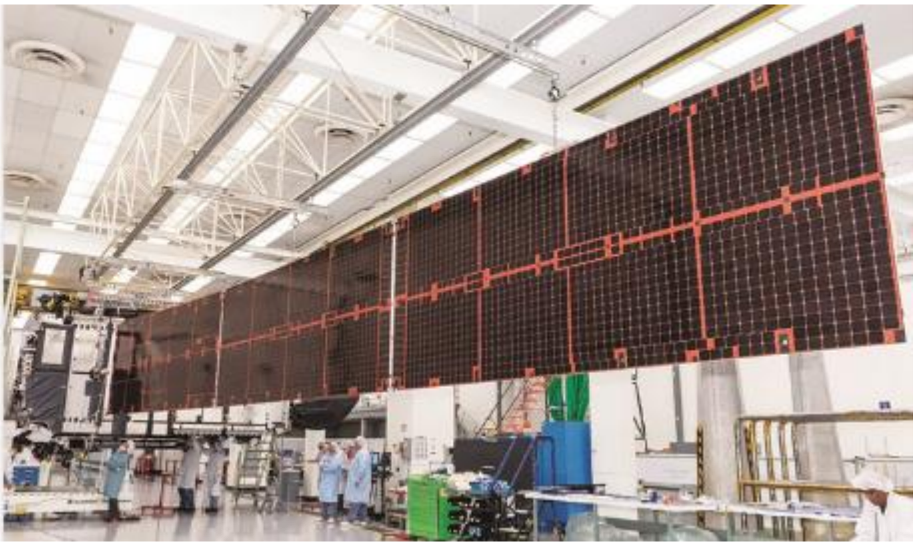


Figure 2-36 Deployable Solar Arrays

The solar arrays of the MR-SP can exploit the know-how matured in TAS in terms of modularity, sandwich construction design, deployment mechanisms, pointing and HDRMs (Hold Down & Release Mechanisms).

As for the truss structures these are considered to be based on CFRP tubular elements with metallic end fittings normally base on Ti alloy also in this case based on TAS heritage.

Figure 2-37 Truss Structure Example

SolSpace

The potential use of inflatable reflectors have been considered based on the experience made with the NASA Inflatable Antenna Experiment performed in 1996 when a 14 m reflector have been deployed from Space Shuttle.

The lenticular inflatable reflector is supported at its periphery by a toroidal structure. The reflector could made of number of metallized membrane gores (e.g. Aluminized Kapton®) bonded together to provide a parabolic-shaped surface. The toroidal part made of curved segments cold bonded together to provide a contour ring.

The main issue is relevant to the inflation and in-orbit rigidization for which a dedicated flight kit is necessary and due to the big size of the reflectors. To this purpose huge amount of foam would be needed and shape precision hardly achievable. The manufacturing of huge inflatable furthermore implies several concerns in terms of handling and joining of large polymeric film areas, repair techniques, efficient ground packaging of big structures.

In this perspective in the SOLSPACE study has been proposed a faceted reflector of a hexagonal shape, constructed using a number of individual tensioned planes of equilateral triangles. This alternative, based on a modular approach can exploit the concepts developed for large solar sails. For this solution a light polymeric film (e.g. Aluminized Kapton® or Mylar®) is tensioned by triangular frames based on CFRP tubular elements providing at the vertices joining nodes for the neighboring triangles, to allow in-orbit assembly. This concept allows real series production and such reflectors could rely on completely existing technologies.

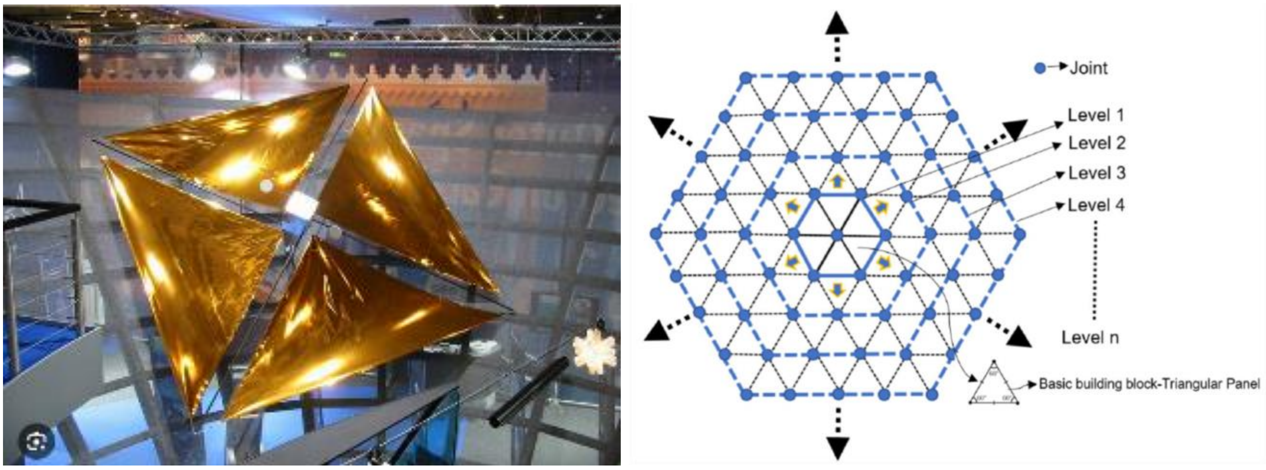
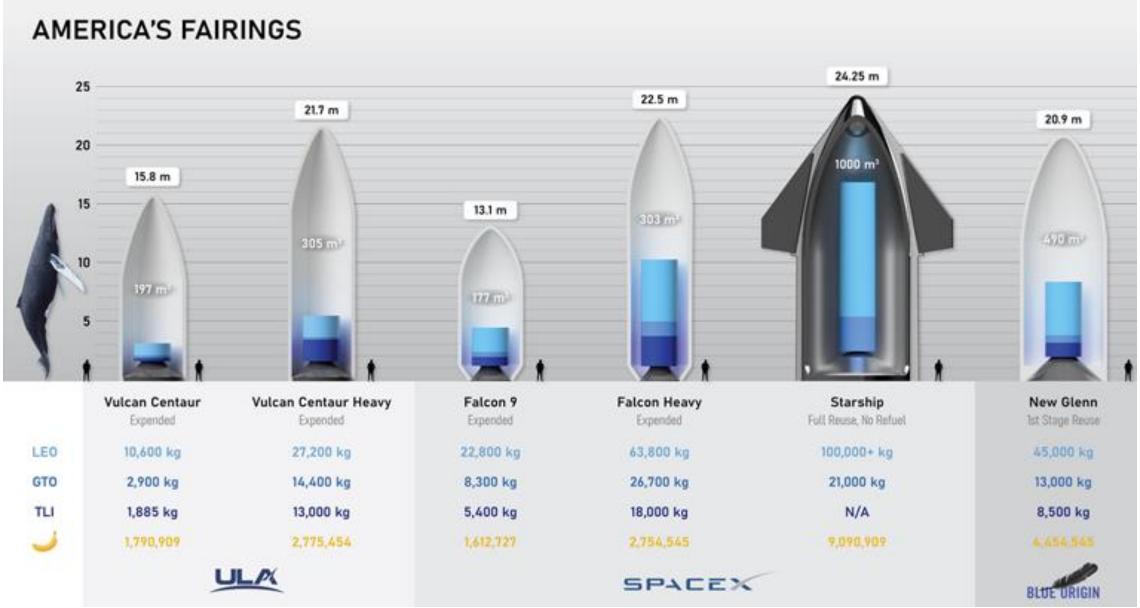


Figure 2-38 Solar Sails (Courtesy of ESA) & SolSpace Concept

Other aspects to be considered for the purpose of a final trade-off, in terms of a preliminary identification of a most promising configuration for the solar panels, looking for structural and material solutions that can maximize, once on-orbit, the energy production in front of a limited number of launches.

The final in-orbit dimensions of the assembled of the SBSP structures have first of all to cope with mass & volume constraints of the current and next generations launchers. As reported in the next picture for US Launchers, the ones currently having the highest payload capabilities:



	Vulcan Centaur Expended	Vulcan Centaur Heavy Expended	Falcon 9 Expended	Falcon Heavy Expended	Starship Full Reuse, No Refuel	New Glenn 1st Stage Reuse
LEO	10,600 kg	27,200 kg	22,800 kg	63,800 kg	100,000+ kg	45,000 kg
GTO	2,900 kg	14,400 kg	8,300 kg	26,700 kg	21,000 kg	13,000 kg
TLI	1,885 kg	13,000 kg	5,400 kg	18,000 kg	N/A	8,500 kg
🍌	1,790,909	2,775,454	1,612,727	2,754,545	9,090,909	4,454,545

Figure 2-39 US Launchers' Payload Capabilities in LEO & GTO

The maximum launchable volume could be reached by SpaceX Starship but with limited mass in GTO: multiple launches are needed in any case.

Based on the launch capability in GTO, it would roughly take an order of magnitude more launches with respect to the ISS (built in about 30 missions), to assemble a SBSP with a kilometre scale, so key features and drivers for structure and materials in the current launchers' scenario are:

- **Structures Modularity**: is necessary to reach final in-orbit dimensions and to cope with the launchers' mass & volume capabilities (each single Structural Module could be individually foldable/deployable)

- **On-orbit assembly:** after deployment each launched payload acts as a Module "building block" concurring to the in-orbit assembly of the SBSP

- **High foldability/stowage at launch**: maximum exploitation of the launchers' mass & volume capability by each Modules

- **Extensive use of lightweight materials**: use of polymeric engineered membranes and CFRP materials with high specific strength/stiffness

- **Modules deployment mechanisms**: operated by extendable truss structures & booms to maximize the extension of the deployed surface, use of energy release hinged joints and mechanism

Depending on the SBSP Concept different type of Module's Structure can be considered. A concept that is here considered more realistic for the hereafter structures and materials discussion is the following one:

Figure 2-40 SBSP Reference Concept

Different typologies of structures are here considered as possible SBSP candidates:

1) Flexible Roll-out Structures

The concept is based on the ISS new Solar Arrays (e.g. ISS Roll Out Solar Array (iROSA)), being based on a flexible substrate and flexible solar cells they can be rolled in a carpet-like configuration for delivery to space in dedicated canisters. The deployment to full size is operated by the strain energy release of rolled booms at the two ends of the structure. The deployed size of is of 16 m length and 6 m width. In terms of materials, the substrate is given by a flexible blanket possibly based on e.g. Kapton/Polyimide with Glass/Kevlar Fabric reinforcement. Each couple of arrays deployed by the lateral booms can represent a single building block module for a SBSP.

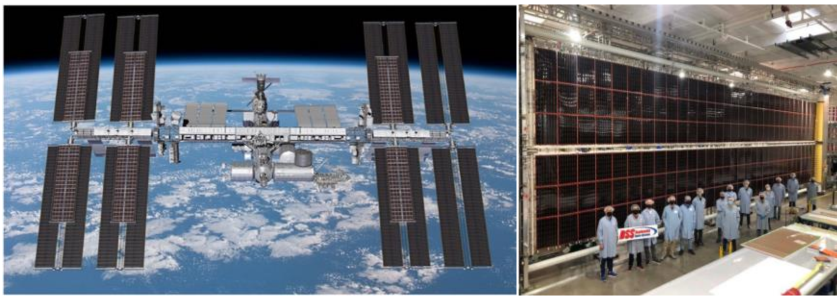


Figure 2-41 iROSA Roll-Out Panels (Credit DSS & NASA)

An analogous concept called SolarFlex arrays has been developed by Thales Alenia Space in France and patented for Space INSPIRE. This is as well a compact solution based on wrapping around a rail just like an automatic roller blind and on a flexible polymeric substrate material. Also in this case each array deployed by the lateral booms can represent a single building block module for a SBSP.

SolarFlex solar array *Thales Alenia Space*

Figure 2-42 SolarFlex Arrays for Space INSPIRE (Thales Alenia Space)

2) Flexible Structures (Circular Modules)

The concept is based on deployable large reflectors with aperture diameters of 35 m and above (https://www.largespace.de/). Different concepts can be used for the deployable backing structure such as umbrella with peripheral rings to tend the substrate supporting the solar cells. The deployment to full size operated by both local actuation with pre-loaded/releasable mechanisms to operate the opening of the supporting backing structure. The substrate can be given by flexible blanket material possibly based on e.g. Aluminized Kapton or Mylar. The circular shape however implies a complex folding at launch of both the support substrate and the attached flexible solar cells which complicates this operation and increase the risks of damaging with respect to linear roll-out solutions.

Each circular array deployed by the backing structure can represent a single building block module for a SBSP.

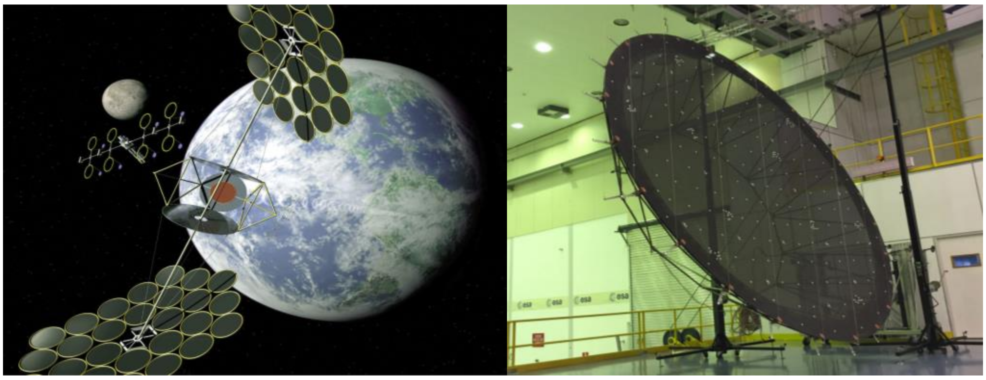


Figure 2-43 Large Deployable Reflectors – Credit LSS

3) Inflatable Structures

For the SBSP purposes the use of inflatable structures could be limited to provide the deployment of the flexible substrate with the attached flexible solar cells and then acting as a frame after rigidization. Depending on the shape, the deployment of the solar array can be operated by inflatable elements: peripheral rings (in case of circular shape), booms (in case of linear or peripheral frame (in case of rectangular shape) as shown hereafter:

Figure 2-44 Inflatable Rings, Booms & Frames – Credit of 'L Garde, ILC Dover & NASA (JPL)

The inflatable structures are based on flexible materials e.g. gas tight Aluminized Kapton/Mylar or pre-pregs composites with an internal gas tight polymeric chamber.

The packaging of complex inflatable structures can jeopardize the correct deployment induced by inflation leading either to local overstressing/puncturing or jamming.

The ultralight nature of these structures and the high packaging capability are also consistently affected by the mass expense for the in-orbit inflation/rigidization system (gas inflation or foam filling systems with the relevant storage reservoirs, feeding lines and valves).

Different types of in-orbit rigidization can be considered e.g. gas inflation, UV curing by sun exposition or heat curing of pre-pregs with heaters (power expense to be considered), filling and hardening of foams but all these techniques with low TRL limited to ground demonstration on breadboards and prototypes.

Risks are also related to ground storage limitations due to the premature curing of the resin system or foam hardening even during the very same manufacturing process: assuring uniform in-orbit curing or complete foam hardening of inflatables is difficult and very likely leading to considerable final shape deviations.

Complex manufacturing due to the dimensions and efficient joining of parts (e.g. long extension of tubular elements requiring segmentation) as a potential source of leakage.

The ultralight nature of these structures is heavily counterbalanced by the mass expense for the inflation/rigidization system (gas inflation system or foam filling system)

Also in this case each array deployed by an inflatable structure can represent a single building block module for a SBSP.

4) Rigid Structures (Polygonal Elements)

The polygonal rigid structures as has been reported above, in the form of tiles, can based on a contour frame to internally support either rigid items or for membranes tensioning purposes.

Depending on the launcher fairing volume, a number of tiles can be hard-connected in a monolithic central part with 2 lateral foldable/deployable monolithic parts to form a Module (e.g. James Webb Telescope -like). Each Polygonal Structure can be manufactured by tubular CFRP elements and depending on the stiffness/strength requirements different carbon fibres can be considered spanning from T300J, to M40J and M55J.

The Modules composed by multiple tiles have to be in-orbit assembled to reach the kilometer scale SPSP. The concept is expressed in the next picture:

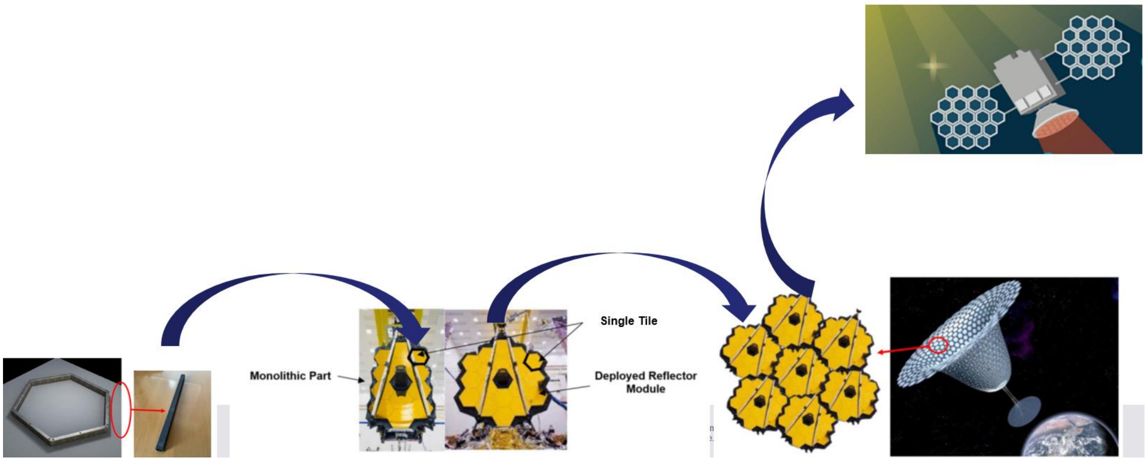


Figure 2-45 Example of Polygonal Rigid Structures for SBSP - Credit NASA

5) Rigid Structures (Sandwich Panels)

In alternative to Polygonal Elements Rigid Structures, the ones based on Sandwich Panels exploit conventional foldable/deployable for satellites solar arrays structures.

Depending on the launcher fairing volume, a number of panels can be launched in folded/stacked configuration and the released/unfolded on-orbit by dedicated HDRMs (Hold Down & Release Mechanism) and hinge mechanisms which already possess high TRL. The sandwich panels which provide substrate for solar cells are based on CFRP skins using T300J, to M40J and M55J fibres in the form of unidirectional materials and fabrics matched with Al alloy honeycomb core to provide bending and transverse shear loads withstanding.

The SBSP modules, each one composed in this case by multiple panels can be furtherly on-orbit assembled up to reaching the required kilometre scale.

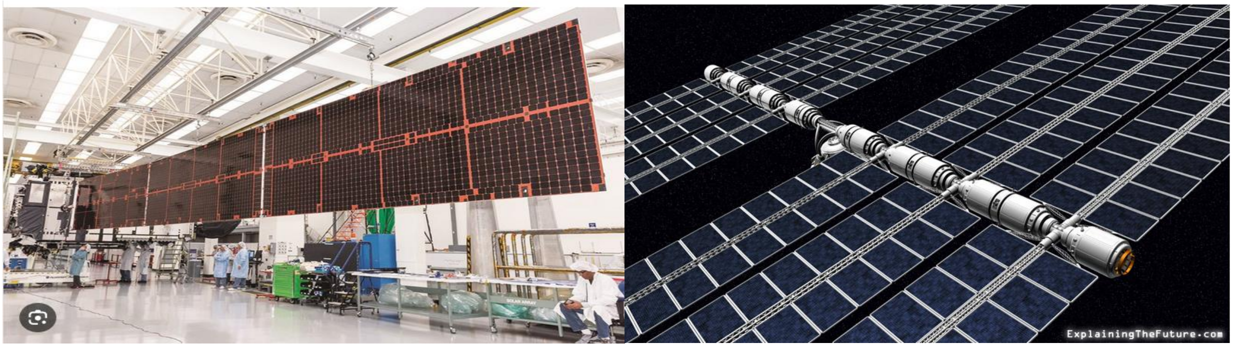


Figure 2-46 Example of Solar Arrays Rigid Sandwich Structures

The above mentioned structural modules based on flexible elements require supporting/deployment structures to provide either unfolding and shaping of the single module or to provide attachment points for the single modules to form the final SBSP. The supporting/deployment structure is not needed for rigid modules where deployment is operated by mechanisms like for traditional solar arrays.

1) Single Module Supporting/Deployment Structures

- **Truss Structures**

These kind of structures is seen for the deployment/extension of circular, polygonal or rectangular membranes with the attached flexible solar cells using for example, in this last case, a pantograph concept. At elementary level they can be based on CFRP materials in the form of square or circular section struts with hinged connections between them to provide folding and deployment capability.

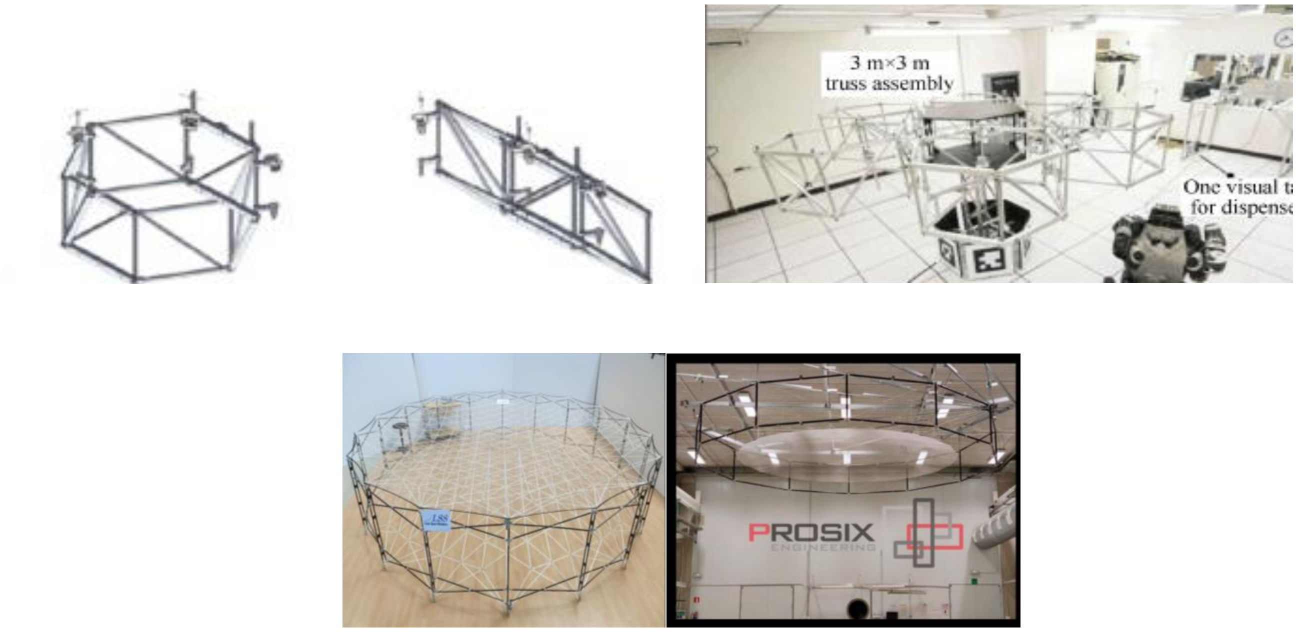


Figure 2-47 Extendable/Deployable Truss for Membrane Single Modules SBSP

- **Booms Structures**

These booms can be efficiently used for the deployment/extension of rectangular membranes supporting flexible solar cells (see above for the roll-out structures). They are based on bi-stable CFRP, Kevlar® or Glass laminates assemblies which are flattened and rolled onto spools for compact stowage within the spacecraft and can be fabricated on specification requirements. They provide passive self-deployment by simple strain energy release and can cover lengths up to 30 m. Multi-Point Spools can be used to deploy polygonal geometries.

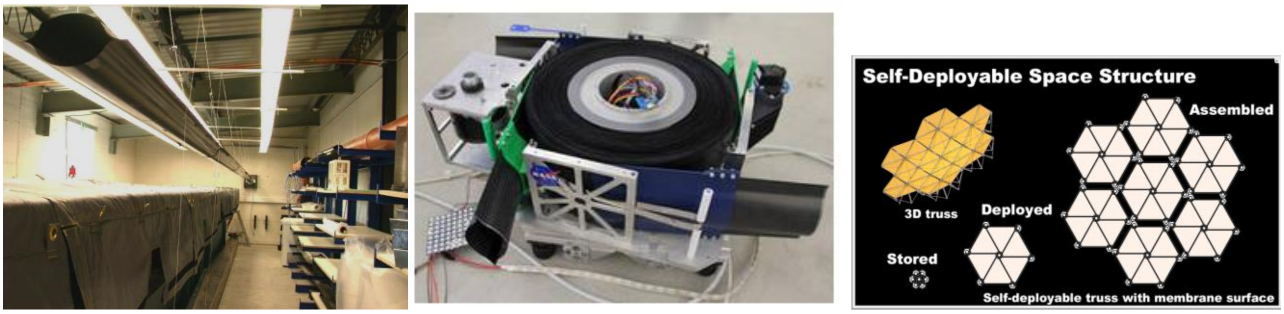


Figure 2-48 Single Point & Multi-Point Spool Booms for Membrane Single Modules SBSP – Credit NASA & CTD

Inflatable booms for the deployment/extension of circular, polygonal or rectangular membranes with the attached solar cells have been also considered above.

2) Multiple Module Supporting/Deployment Structures

- **Truss Structures**

These kind of structures can offer after their extension, attachment points for the single SBSP modules. They can be based on launch folded truss segments to be deployed and joined on-orbit in order to cover the final need in terms of population with all the required modules.

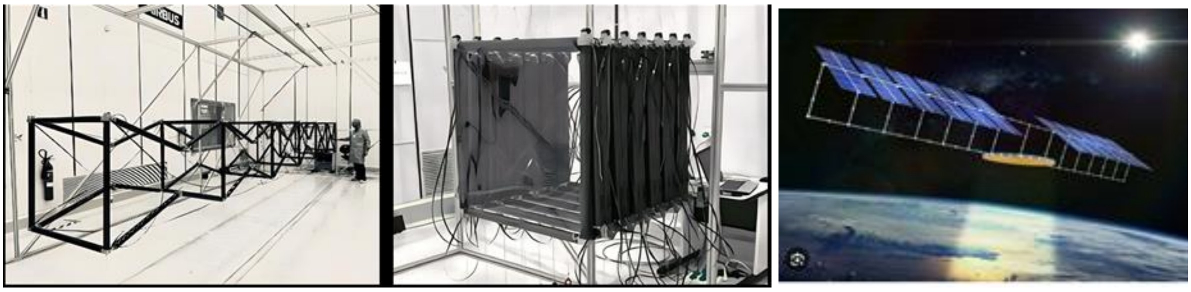


Figure 2-49 Extendable Truss – Credit Prosix

In synthesis for the considered structures:

Flexible Roll-out Structures: look the most promising ones in terms of available technologies and TRL (already in-service for the ISS 2nd generation solar arrays) including the deployment system based on coiled booms.

Rigid Structures: there is a yearly experience in managing large solar arrays with the relevant HDRMs & deployment mechanisms.

Inflatable Structures: low TRL is associated with these solutions with several drawbacks related to safe deployment and in-orbit rigidization (several techniques potentially available but requiring heavy development including ground testing).

The highest TRL is relevant to Roll-Out (ISS experience) & Rigid Structures (satellites solar panels). The Roll-Out Structures having higher compaction and mass optimization at launch wrt to the Rigid Structures.

For all the examined SBSP structures: modularity and on-orbit robotic assembly has to be considered.

2.8 Thermal materials and management

Purpose of the Satellite Thermal Management is to keep the components within their allowed temperature ranges (for operation and survival), rejecting the waste heat and accommodating the thermal transient during eclipse phases.

Given the the required size of a Solar Power Satellite (SPS), one of the main design constraint is a modular approach, scalable from small prototypes for testing, to larger sizes that can be assembled and/or manufactured on orbit [RD3]. From the thermal management point of view, this means that each module should be equipped with an integrated thermal control system. The modules composing the SPS may vary in shape, size and thermal properties (solar array, concentrators, space antenna) and each of these should be assessed from the thermal point of view considering its peculiar characteristics and properly evaluated in terms of allowable temperature limits, external environmental conditions, control of thermal parameters and definition of associated technologies relevant to the thermal control [RD25].

No specific figure has been defined so far in the frame of this study for the thermal heat load to be managed, however a design solution with passive thermal control system is normally considered in literature. Passive thermal control is generally preferred for mass reduction and reliability due to the possibility of avoiding single points of failure [RD1].

Considering the very large size of the system, the rear side of the solar array is intrinsically able to act as a radiator. For instance, MR-SPS presents a non-concentrator modular concept, with a solar array module made of high efficiency thin-film GaAs cells, where heat control is achieved by the choice of high thermal conductivity materials and lightweight radiation hardening insulation materials [RD11].

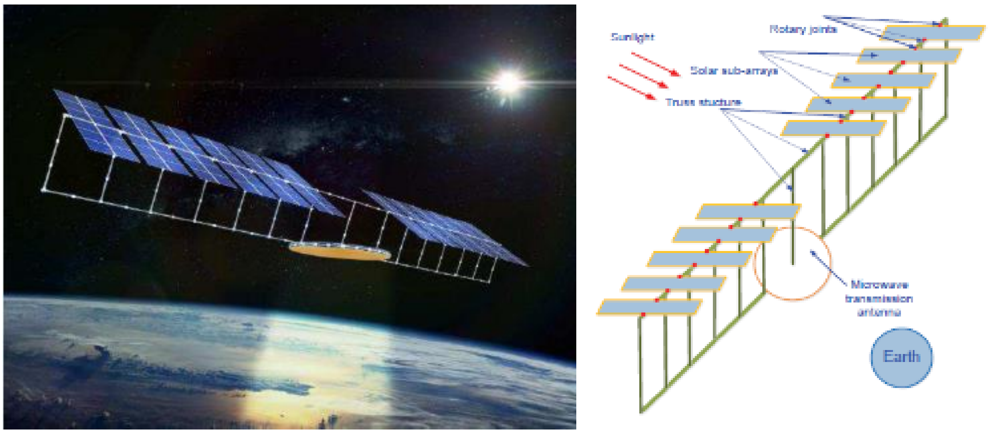


Figure 2-50 MR-SPS design concept with light high efficiency thin film PV cells

CASSIoPeiA consists of a helical structure with High Concentration solar Photovoltaic panels orientated to face solar North and South, to collect light reflected by reflectors. Also CASSIOPeiA has been designed around 100% passive radiative cooling, without the use of fluid filled radiators: a thermal conductive layer beneath the Concentrate PhotoVoltaics cells provides sufficient spreading and re-radiation of waste heat [RD7].

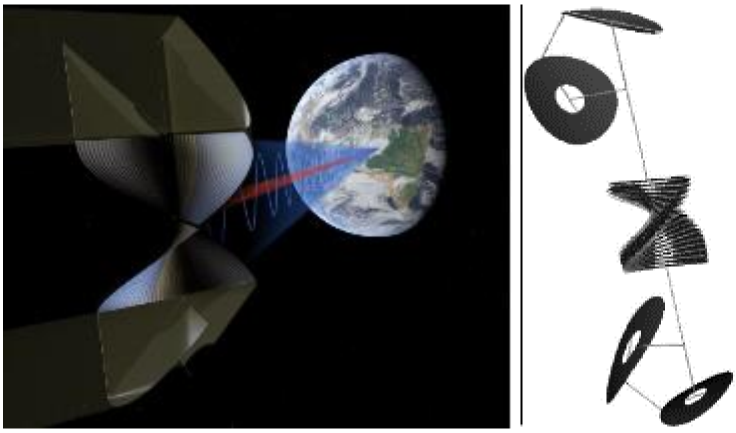


Figure 2-51 CASSIOPeiA design concept, with 4-sun symmetrical concentrator on the right

Assuming adequate thermal conductivity and emissivity approaching black-body, the mean temperature at points across the CASSIOPeiA body can be found by applying the Stephan Boltzmann equation:

$$\frac{P}{A} = \sigma \times T^4$$

where P the incident power (W), A is the total surface area (m2), T is the kelvin temperature and σ is the Stefan-Boltzmann constant. Considering the refrigerative effect of microwave beaming, the worst case mean temperature for CASSIOPeiA will reach 70-90°C depending on the concentration of sunlight factor [RD6], with a maximum temperature on the PV cells of 180°C [RD2]. Therefore the thermal limits of PV cells is a design constraint to be accounted for during the choice of materials.

Of course, to evaluate in detail the view factor of a SBSP element to its radiative sinks and thus the actual heat rejection capability, a sufficiently consolidated design configuration is required.

SPS-ALPHA, is a Sun-pointing concentrator design. The reflectors in this design are motorised and can be independently adjusted with the relative change in position to the Sun to reflect light onto the photovoltaics in the sandwich panel. This allows the satellite operator to control the amount of light hitting the panels by changing the position of the heliostats, which is useful to control thermal load. In the design presented into [RD3] there are no cooling loops or radiators. The only interfaces between the modules are mechanical connections and wireless communications, therefore each of the SPS-alpha module shall incorporates thermal control features.

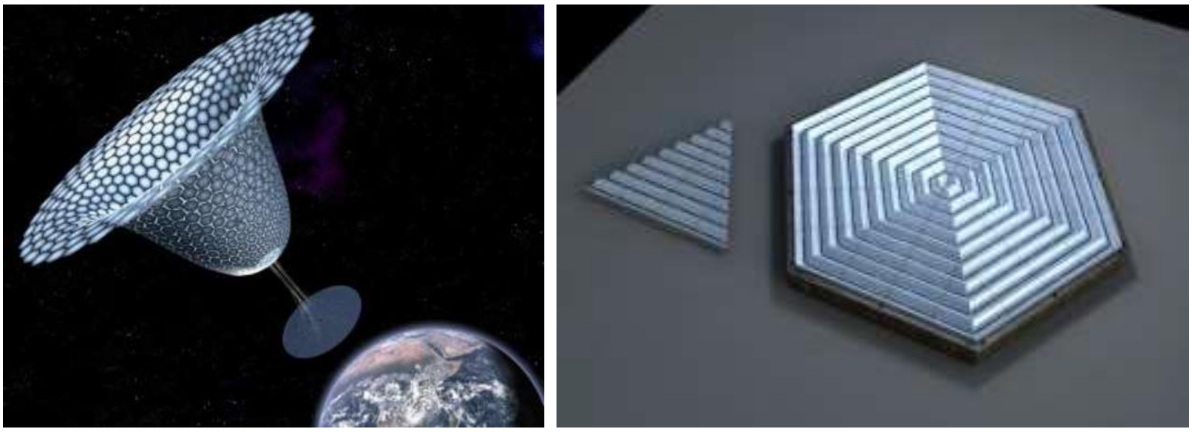


Figure 2-52 SPS-alpha design concept, with thin-film reflectors organized in the extremely large reflector array (left). Solar power generation element concept, incorporating PV cells with integrated thermal control (right).

Currently, no reference to the thermal management of the antenna module is found in the available literature. In principle, the orbit is controlled by the AOCS to keep the solar array Sun-pointing and the antenna Earth-pointing, therefore the rear face of the antenna which is not active, could be considered for thermal control purposes. Thermal control could be implemented with a network of heat pipes and/or loop heat pipes connecting the electronics to a radiator. Current technology developments already foresee deployable radiators integrated with flexible-loop heat pipes for heat transport, to be scaled up according to the power load and sizing of the specific application.

As standard practice, use of thermal conductive materials at the electronics mounting I/F can be foreseen (thermal filler like cho-foil and sigraflex)

However, for high power electric devices, enhanced cooling is needed. For narrow temperature range devices, for example, electric power conversion devices, microwave generators and storage batteries, an active thermal management could be needed, although not foreseen in the projects revised so far (SPS-alpha, Cassiopeia, MR-SPS)

In conclusion, the Thermal Management is one of the main technical challenges and a detailed configuration of the system is necessary to define the thermal system design, by proper definition of the heat load to be rejected, the maximum temperature limits of the PV cells and the electronics, and the concentration of the solar flux on solar arrays and radiators, if present.

Nevertheless, thermal management is feasible and the following key points can be already outlined for the design solution.

A modular approach is necessary due to the large size of the system and the need for on-orbit manufacturing and assembly.

For mass reduction purposes, the design shall rely on passive thermal control to the maximum extent, possibly implementing LHPs for specific units.

Thermal control of solar arrays can be achieved considering a rear side solar panel acting as its own radiator, by a proper choice of lightweight high-conductance materials.

Finally a radiator design concept is proposed for thermal control of the antenna. A deployable or inflatable configuration, integrated with LHPs, is identified to control the thermal gradient between radiator and electronics, while allowing proper orientation to maximize the effective radiating area and reduce impingement.

2.9 In-Space transportation and infrastructure

The size of the SPS dictates how a sequence of launches to transport all the required assembly parts to the final (or assembly) orbit are required. The infrastructure building blocks and modules will be designed for efficient packing in the fairing of the chosen launch system and then subsequent autonomous in-orbit deployment and assembly.

Two main strategy may be followed to deliver the systems to the final orbit:

- transportation and assembly directly in the operative orbit
- transportation in a parking orbit, orbit raising and assembly to the operative orbit

The choice of delivery orbit, assembly orbit and transfer orbit will depend on a number of factors, such as the location of the final orbit, the capacity of the selected launch vehicle(s), modularity of the infrastructure, type of assembly (docking versus robotic assisted) and it will be the results of a dedicated trade-off aimed to optimize the overall cost, assembly duration and complexity.

If the proposed final orbit is in LEO/MEO, it is safe to assume that the transportation and assembly will be performed directly in the operative orbit, as using a parking orbit would bring no advantage. Moreover, building directly in the operative orbit have the added benefit of being able to perform energy transfer operations while the satellite is being built.

In case of a Molniya orbit as the chosen orbit, using a LEO/MEO orbit as parking orbit can be considered. This concept will require an orbital tug that shall be able to perform rendezvous and mating manoeuvers, as well as orbit raising maneuvers to bring SPS to its operational orbit. Both chemical and electrical propulsion can be considered for this task. The main advantage of the chemical propulsion would be the reduced time required for the orbit raising, while the electrical propulsion will require little fuel compared to the chemical counterpart in exchange of a lower thrust for the same size. Propellant tanks shall be sized accordingly. Thus the main constraint of this configuration lies in the propellant system size and mass. Moreover, due to the dimensions of SPS, a detailed structural analysis shall be conducted to ensure that during the raising maneuver the vibrations suffered by the SPS will not cause failures. Building directly in the final orbit will allow a smaller tug propulsion system as it will be required only for assembly maneuvers at the cost of a higher amount of launches.

For the GEO as operational orbit, a similar reasoning as the Molniya orbit can be conducted. Another potential transfer orbit in this configuration is the GTO, which will require lower Delta V to bring the SPS to its operational orbit compared to the LEO/MEO case, again at the price of a higher amount of launches required.

From this preliminary evaluation, it appears clear how the choice will be based mainly on the launcher and propulsion system performances. The TRL on heavy lift reusable launchers and on high-thrust electric propulsion system will move the needle of the scale on the usage of a parking orbit or directly injection in the satellite's operational orbit.

2.10 Platform systems

The SPS platform is typically composed of:

- Energy chain (to convert and transmit power)
- Structure
- Thermal Management
- AOCS
- Communication system
- Electrical Power system
- Data Handling system

Subsystem	Current TRL	Comments
Energy chain (power transmission)	3-4	WPT technology application in the space domain has been recently proven by Caltech through the MAPLE experiment but need to be tested at higher power and altitudes. Particular attention in R&D could be concentrated for the DC-RF and RF-DC converter technologies in order to rise their efficiencies (which are drivers for the SBSP power trasmission chain together with the PV cell efficiency)
Energy chain (power conversion)	6	PV (normal or concentrated) cells need to reach higher efficiencies with respect to actual technologies already flight proven (30% proven, 36% expected). However some very high efficiencies have been proved in laboratories for four or more junction cells
Structure	6-7	Roll-out structures have an high TRL (9) having already some applications for example with ROSA panels (ISS). However some problems could emerge when scaling up the system, in particular for the rotation of these panels

Thermal management	6-7	Passive thermal management is required for the solution so the majority of the technology needed is proven (TRL 9), while considering that there could be some problems when scaling up the system as in our case (thermal loads from PV cells, DC-RF generators and electrical thrusters)
AOCS	5-6	The use of Hall thrusters in order to counteract the solar wind (order of N of force) at the moment would require thousands of thrusters (single one has an order of mN thrust, with current technology). However studies are already in place to develop possible thrusters with higher thrust density, so that the needed number could be lower. The other technologies for AOCS can be considered quite standard so with a very high TRL
Communication system	7-8	Typical communication system needed in high orbits but could require some particular commands encryption (QKD –ESA mission in LEO in 2023 and papers to study possible future developments for GEO)
Electrical Power system	4	The Electrical Power System is based on a wide heritage due to the high technological maturity of EPS equipment. Nevertheless, the huge power involved in this application makes necessary to manage very high voltage ranges. With this purpose, it is needed to consider more performant power conversion technologies (currently with a low TRL). Anyway it is expected that the efforts to push this solution to space application market will be considerable.

Table 2-7 SPS platform systems

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