SOLAR POWER SATELLITES
SPS-REPOSE

System feasibility assessment
(WP 1000)

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SUMMARY

This technical note summarises the work done in the WP 1000. It has been prepared by the SPS-REPOSE team with EADS-Astrium, Université La Réunion and Technicatome.

At first, a review of the existing studies on the Space-to-Earth power transmission is carried out in order to highlight the main features.

Then, the technical note reviews the main elements of the Space-to-Space power delivery system that means the power collection and distribution, the laser power transmission system and the RF power transmission system. Both power transmission systems include the beam generator equipment and the associated receiver system. A review of the possible laser system approaches (single lased, space based laser arrays) as well as of the possible technologies as function of the wavelengths has bee done. A review of the candidate thermal energy conversion system is also carried out. For the RF power transmission system, a review of the main parameters driving the size of the system, of the possible frequencies and of the technologies for the beam generation has been done. Preliminary selection of candidate systems and technologies is proposed, for an assessment wit respect to different mission cases.

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1 INTRODUCTION

Power generation is one of the crucial elements of space vehicles as well as of elements implemented on other planets. It is a main contributor of the mass, size and cost. The on-board available energy is limited by the mass and size of the vehicle and by the launcher constraints, although the improvement of the technologies (solar cells, storage systems, etc) allows an increase of the power system performances (efficiency, energy density). Furthermore, the sizing of the power generation system is driven by the eclipse period, requiring storage system and solar arrays surface for batteries recharging, by the environment and by the solar irradiation intensity.

New systems and technologies have to be found. The power transmission from a Solar Power Satellite is an attractive solution, applicable to all the space missions and to the delivery of power to Earth sites as well. It is based on Wireless Power Transmission concept.

Studies have been carried out for tens of years on providing renewable electrical energy on Earth from Space Power Satellites. Targeted range of electrical power is from hundred MW up to several GW.

Most of the proposed systems relies on RF power transmission at 2.45 GHz or 5.8 GHz to cope with the atmospheric attenuation and existing technologies while minimizing the size of the transmitting antenna. Being on ground, the receiver system is not constrained by its size. Nevertheless, maximum energy density is driven by the safety rules and receiver antenna technology. Providing power to space vehicles or elements on other planets will lead to some different constraints: the level of required power is drastically lower, the environment is different (no atmosphere, except for elements on Mars), the size allowed for the receiver system is limited.

Space-to-Earth power delivery systems include a constellation of SPS to take into account the non-visibility periods. Same problem may occur according to the space target.

This technical note aims to overview the Space-to-Earth systems and applicability to Space-to-Space systems, and to review the possible laser and RF power transmission systems, their technologies for a range of expected power and distances, as well as the power generation candidate solutions.

2 SYSTEM ASPECTS

2.1 SYSTEM OVERVIEW

The power delivery system is illustrated on Figure 2/1. It is composed of:

- The power generation system (solar cells, concentrators or other)
- The power transmission system, including the conversion of electrical energy into RF or laser signal and the generation of the beam
- The power receiver system, including the conversion of the received signal into electrical power.

Key parameters of the power delivery system are:

- The frequency (or wavelength) of the power transmission system. The two options are the laser or the RF transmission, for which different frequencies can be considered.
- The power to be provided to the target
- The distance between the SPS and the target.

These parameters depend on the mission case:

- The required power is imposed by the target
- The type of transmission system may be induced by the target constraints or environment: for instance, the reuse of solar cells as receiver system leads to a laser power system (even in the sunlight wavelength), the Mars atmosphere and dust storm induces the use of RF system, etc. Nevertheless, in some mission cases, the choice is open
- The distance is also linked to the positioning of the SPS, itself depending on the target position.

The key features of the power delivery system are listed in the Figure 2/2. They described a system, with:

- The location and orientation of the SPS
- the selected type of transmission system and associated beam frequency or wavelength,
- the power to be generated and the generation system
- the power transmission system: conversion electrical power to signal, beam generator and transmission (antenna or laser size, system mass, steering capability, etc)
- the receiver system, and the conversion to electrical power (size and mass, efficiency, etc)
- the power density at target
- the end-to-end efficiency. The overall efficiency of the system will be a main driver for the assessment of the candidate systems. This efficiency includes the efficiency of the power generation, the efficiency of the conversion from electrical power to transmission signal, the efficiency of the transmission system (antenna or laser), the attenuation of the beam (if any), the energy received by the receiver system (as compared to generated energy, function of the beam size at target level), the efficiency of the receiver conversion system. This overall efficiency will drive the size of the power generation system.

The mass of the power transmission system is also a characteristic of the system, already covered by the above features. It includes the power generation and the transmission system. The mass and size of the receiver system will impact the target. Both shall be considered in the selection of the system.

The features of the power delivery system are driven by the technologies, which could be selected. Indeed, different technology options may be considered for each element of the power delivery system.

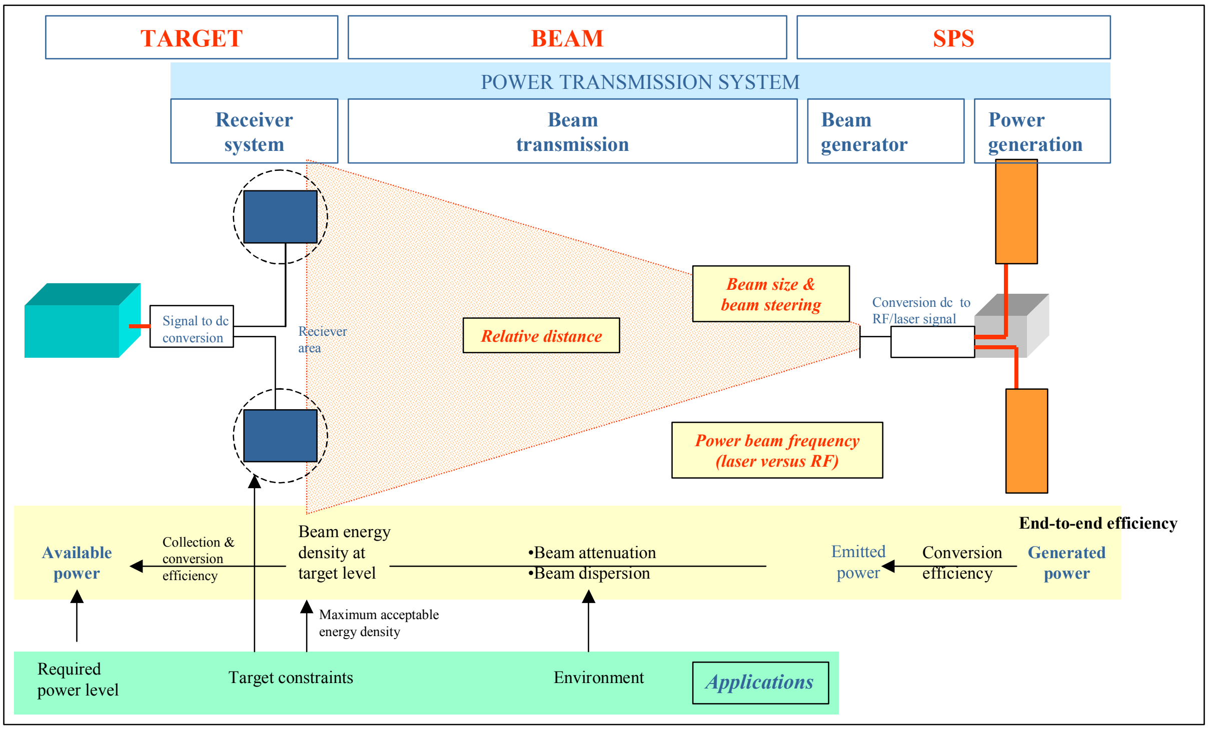


Figure 2/1: Illustration of main elements of power delivery system

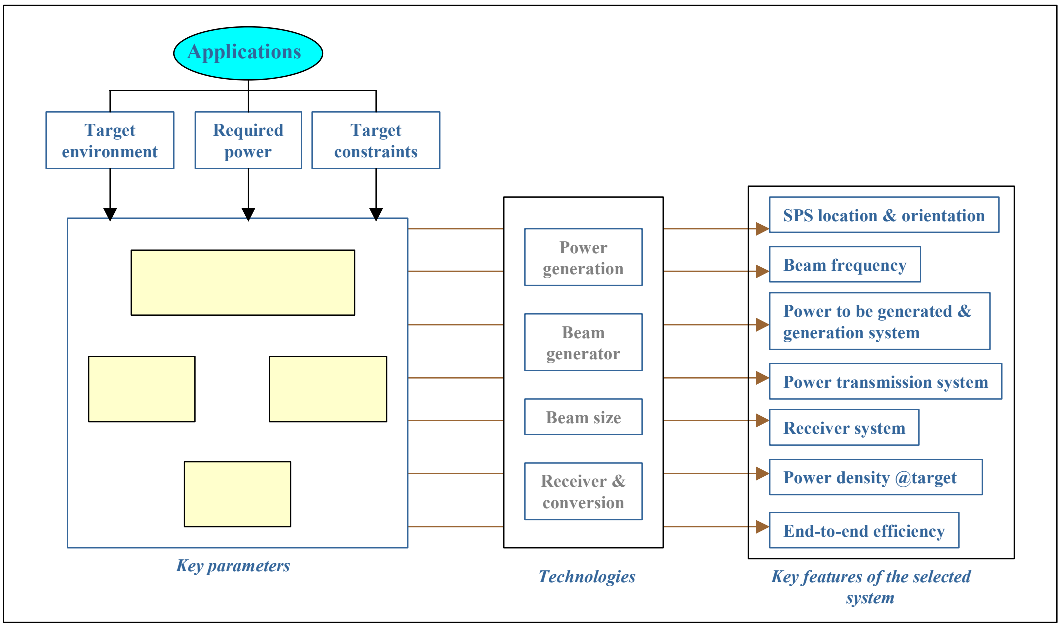


Figure 2/2: Key features of the power delivery system

The selected option will depend on the mission case (and thus on the above-mentioned key parameters). These technology options are summarized in the Figure 2/3.

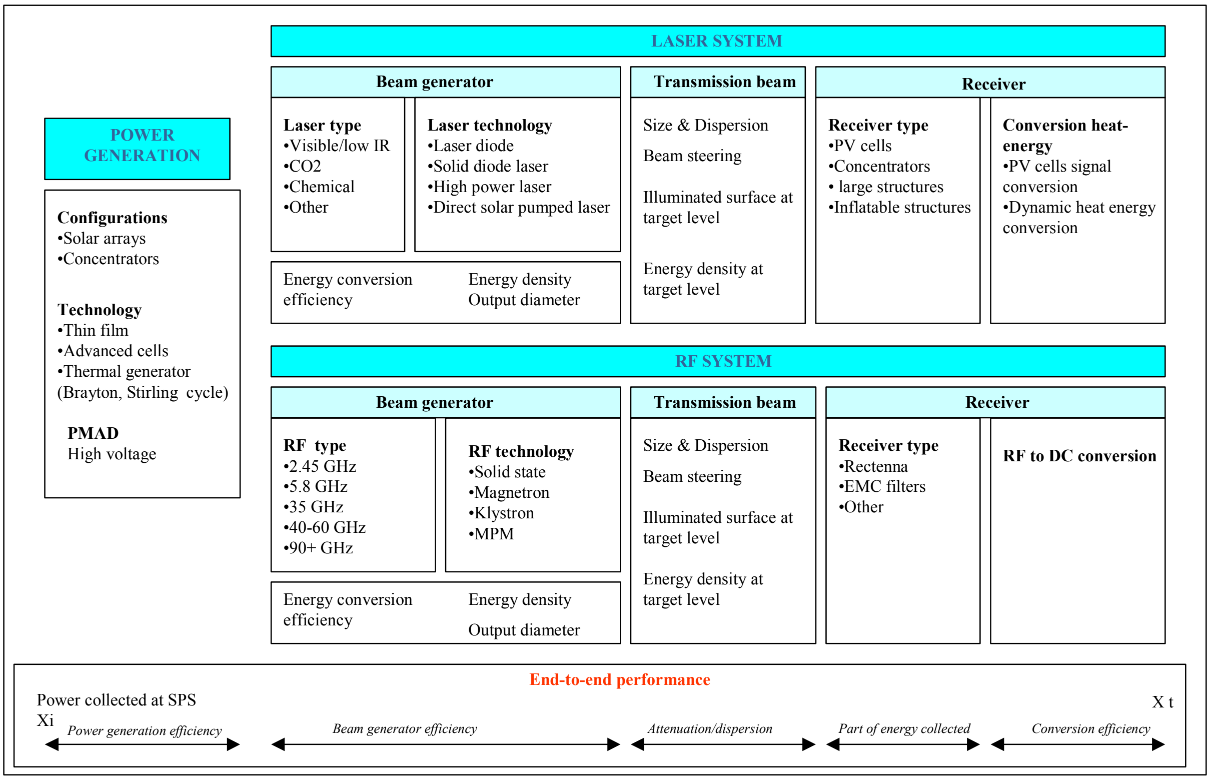


Figure 2/3: Power delivery system overview and technology options

2.2 RANGE OF NEEDS

The potential applications have different needs and constraints in term of power level, target trajectory, time at which the power is needed, etc. In order to review and assess the main power transmission system options and technologies, a preliminary review of the possible applications range of needs has to be done.

The following table 2.2/1 gives the range of the main parameters for the three categories of mission: the power delivery to Earth orbiting platforms, to interplanetary vehicles, and to planetary elements.

CASE	EARTH ORBITING PF	EARTH ORBITING PF	INTERPLANETARY MISSIONS	PLANETARY SURFACE MISSION
Application	GEO satellite	LEO platform	Interplanetary vehicle	Element on Mars
Needed Power (kW)	20	20/ a few 100	0.5 / 50 / a few 100	1/ a few 100
SPS Positioning	LEO Sun synchronous/ Slightly beyond GEO	GEO/ Lagrangian points	Earth orbit / Moon/ Lagrangian points	Mars GEO orbit
Distance SPS-target (Km)	~ 45000/ 10000 to 20000	30000 to 45000/ > 1 Million	> 100 000 > 1 Million	20 000

Table 2.2/1: Range of needs for the three categories of mission

3 OVERVIEW OF EXISTING SPACE-TO-EARTH CONCEPTS

Studies have been carried out on Space-to-Earth power transmission systems in USA, Japan and Europe.

Although the target (more or less large area on Earth) is well identified, different concepts have been proposed and refined for this application. They differ by the range of provided power, the location of the SPS and subsequent relative distance, the pointing of the solar generators or antenna for power transmission. Most of the concepts rely on an RF power beam. Last, but not least, there is no constraint on the size of the receiver system as it is implemented on Earth.

A review of some of them has been done in order to identify the rationale of their configuration, and compare their sizing. It also allows to assess the evolution of transmitting antenna size and SPS mass as function of user required power or relative distance.

The following concepts have been reviewed:

- The Sun Tower configuration: in LEO and MEO, and with the support of a relay
- The Solar Disc concept, in GEO
- The Abacus reflector, in GEO
- The integrated Symmetrical Concentrator, in GEO
- Halo
- The European Sail Tower

All these systems assume a constellation of satellites in order to fulfil the power requirements. The review is focused on the single satellite.

3.1 SUN TOWER CONCEPT

3.1.1 Orbital location

Several orbital locations have been considered for the Sun Tower concept along the successive studies:

- LEO Sun Synchronous (SSO)

  The power required by the user was 50 MW. The SPS was at an altitude between 600 and 1400 Km and at 98° inclination. The solar collector was always facing sun, leading to a simple design for the power generation. The main drawback of this orbit is a short period of visibility of the ground target, leading to a few tens of minutes per day of power delivery to a given ground area.

- MEO

  The power required by the user was 250 MW. The SPS orbit inclination was in the range 30-50° and the altitude between 6000 and 20000 Km. The interest of this orbit was to increase the power delivery time per day to several hours. The drawback is an increased distance, a more difficult radiation environment and more complex manoeuvres with possibly rotating solar panels.

Besides, the SPS met periods of eclipse.

- GEO

  The GEO orbit has been selected to ensure a permanent availability of power on the ground site. Nevertheless, on this orbit, the SPS has daily eclipse periods around the equinoxes. Power storage is sized for this period. The main drawback is the distance (in order of 36 000 to 40 000 Km). A much larger transmitter and power generation is required, that has impact on the SPS configuration length and cabling.

3.1.2 Satellite configuration

The Sun Tower space segment concept is illustrated in Figure 3.1/1 and 3.1/2. The SPS configuration is like a tower, and is gravity gradient stabilized. In GEO, the solar panels are rotating (two axis?) for sun tracking, as the SPS remains oriented towards the ground site. Rotating individually each panel may lead to problem of partial or full shadowing of some panels by others.

The size of the SPS is approximately 15 Km long and 0.2 Km wide. Its mass is:

- 530 t in LEO (50 MW at user)
- 3500 t in MEO (250 MW at user)

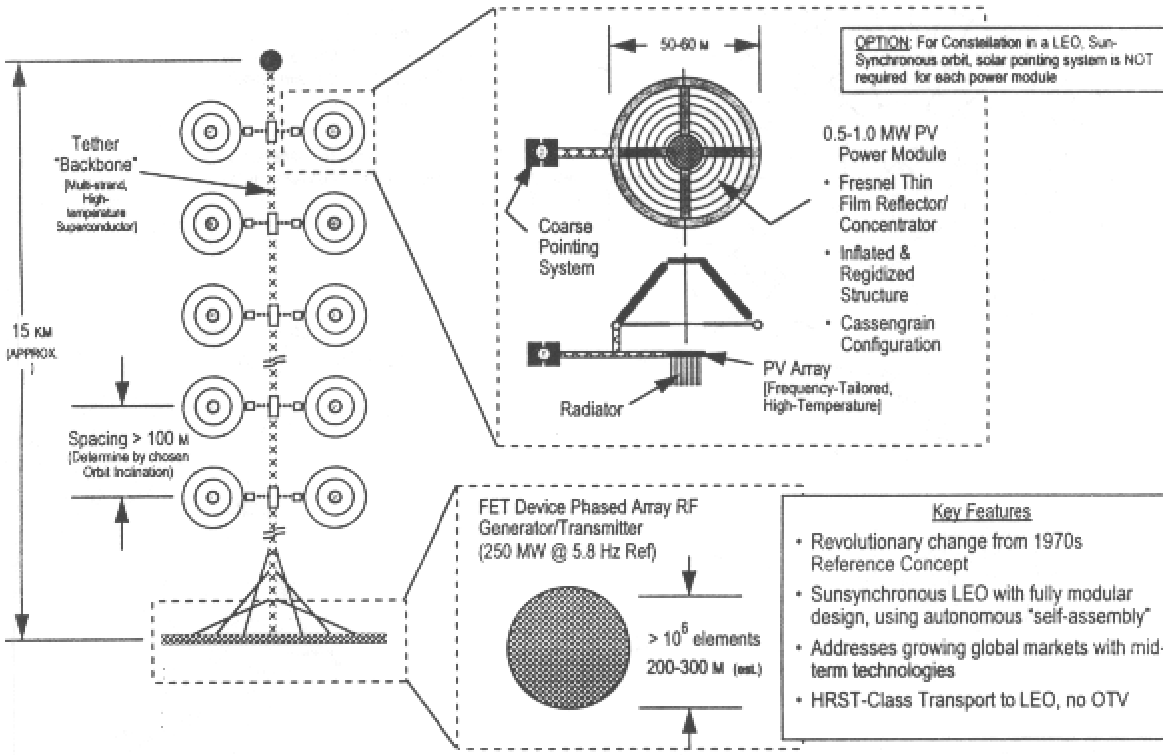


Figure 3.1/1: Sun Tower concept (from NASA Sun Tower concept (NASA Fresh Look study, 1995)

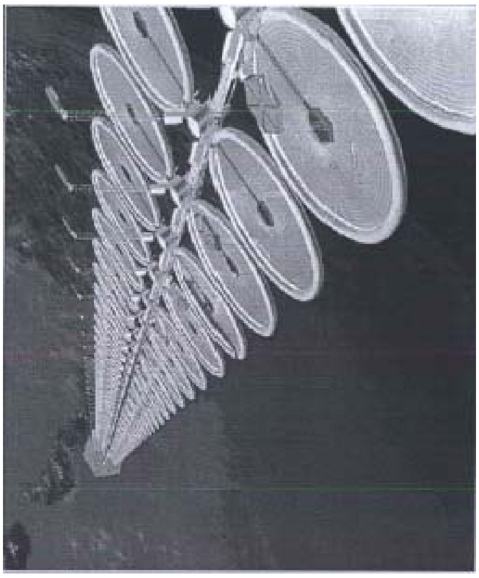


Figure 3.1/2: Illustration of Sun Tower concept (from NASA Sun Tower concept (NASA Fresh Look study, 1995))

3.1.3 Power generation system

The system is composed of a number of units attached per pair along a modular tether backbone. The number of pairs of units depends on the orbital location and user required power.

A minimum spacing (higher than 100 m) between the units is determined as function of the inclination, to avoid shadowing from a unit to the other.

Each unit includes a solar collector of 75 m diameter and is able of delivering a net 1.3 MW electrical output. The collector is a Gossamer self deploying (inflatable) structure based reflector with advanced photovoltaic element. Each unit includes also a modular radiator ensuring the heat rejection for the power conversion.

The power is then transferred to the power transmitting system via the backbone.

As example, for MEO application, the SPS includes 340 pairs of solar collectors and the relevant backbone length is 15 Km.

Being able to grow only in one dimension, it has long, heavy cabling running tens of Km.Besides, in this configuration, an enormous amount of electrical power has to be passed through a massive rotating joint.

3.1.4 Transmission frequency

The power transmission system relies on RF system at 5.8 GHz, from 1400 Km (SSO) or 6000 Km (MEO).

Comparison between 2.45 and 5.8 GHz was done. For example, to deliver 50 MW from SSO (1400 Km):

Frequency (GHz)	2.45	5.8
Planar array diameter (m)	250	106
Rectenna diameter (m)	2500	2000

- The larger array required at 2.45 GHz, for the same output power, leads to narrowing the normally wider beam produced, with impact on rectenna diameter (not much larger than at 5.8 GHz).
- For attenuation, there is a higher susceptibility to rain at 5.8 GHz. However, the delivered power would be lowered by about 1/3 dB for a heavy rain (2.5 cm/h).

Therefore, the 5.8 GHz was selected with respect to 2.45 GHz to reduce the required size of both the transmitting and the receiving area at the higher frequency, or to limit the size of in-space transmitting array for a given beam spot size on Earth, while minimizing atmospheric attenuation.

3.1.5 Transmitting system

The transmitting array is made of sub assembly of single elements.

The single element has an hexagonal surface, a diameter lower than 4 cm, and is capable of:

- 12.5 W input power level @ 80% efficiency
- 10 W output power for transmission.

A subassembly is fed by a pair of power generation units (modular power transmitter).

The transmitter array diameter is 106 m for 50 MW in SSO, 260 m for 250 MW in MEO. To provide 250 MW, it includes more than 1 Million of single elements. The power distribution grid, implemented on the array backplane, has a thickness of about 1m. A modular heat rejection is integrated in the backplane.

The beam generation is done by using solid state FET devices instead of magnetron tubes:

- The solid state FET devices provides 10W @ 80% efficiency and @ 5.8 GHz
- The magnetron provides 5 kW @ 90% efficiency and @ 2.45 GHz. It seemed difficult to design magnetron arrays operating @5.8 GHz due to heat removal for high power devices.

3.1.6 Beam steering

A beam steering capability was found necessary to provide service to several ground sites, or to have a greater contact time with a single transmitter, especially in SSO or MEO. It has an important role, as the limitation of the contact time is function of the maximum slew angle.

Electronic beam steering was preferred to mechanical beam steering to reduce drag and cross section exposed to micrometeoroids.

The maximum single element size is inversely related to the transmission frequency and the maximum beam slew angle. The element size together with the power produced per element determines the maximum array size for specified output power.

The maximum beam slew angle is +/- 30°.

3.1.7 Receiver

The receiver system on ground is a planar rectenna, which has a diameter of 2 Km for a SPS in SSO, and 4.5 Km for a SPS in MEO.

3.2 SUN TOWER CONCEPT WITH A RELAY

The main drawback of the Sun Tower in LEO was the low percentage of visibility between the SPS and the ground site. A permanent coverage of the ground site requires a constellation of SPS. The utilisation of a relay aims to improve drastically the availability of the power transmitted by a single SPS on the ground site. The relay has been considered in MEO or in GEO.

Two approaches have been considered for the transmission by the relay to the ground sites of the energy received from the SPS: the frequency conversion, or the reflect arrays.

3.2.1 Relay satellite based on Reflect arrays

On this concept, the same frequency is used for incoming and outgoing power (2.45 to 30 GHz).

To that aim, the relay satellite is based on a planar, RF power reflecting array. This array uses a phase shifting approach for beam forming and for redirecting the illuminating RF power.

The advantages of this approach with respect to the frequency conversion are the efficiency and the pointing and operational simplicity.

Both SPS and relay array diameters have to be increased with respect to the frequency conversion approach. For instance, with a relay in GEO, the reflect array diameter should be 3 Km or more to provide beam coupling to a transmitter array with diameter of 0.8 to 1 Km.

The beam coupling efficiency is the major performance of the relay based concepts. The diameter of the power receiver/reflector of the relay is preferably kept small, that is detrimental to the beam coupling efficiency, as a smaller fraction of transmitted beam is captured. Besides, it leads to a large spot size on ground, requiring larger rectenna. An increase of power and diameter of the SPS transmitting array is an option to narrow the beam, but is limited by SPS constraints.

Thus, with a relay in MEO (LEO to MEO), the nominal ground rectenna has a diameter of 2 Km. With a relay in GEO (LEO to GEO), the ground rectenna diameter is 3 Km.

3.2.2 Relay satellite based on frequency conversion (alternative)

The transmission between SPS and relay on one part, and between relay and ground site on another part are at different frequencies.

The space-to-space transmission could be in mm-wave (typically 245 GHz) for better transmission (higher beam coupling efficiency) while the relay-to-Earth transmission remains in µ-wave.

The transmitting array diameter is of about 150m for a range of about 15000 Km. The relay satellite has two steerable receiving antennas, each of about 120m diameter. The power received from the SPS is stored on-board, or converted to µ-wave frequency (5.87 GHz) and transmitted to Earth via planar antenna of 240m diameter.

3.3 SOLARDISC CONCEPT

This concept involves an extensively axisymmetric and modular space segment based in GEO. The SPS is illustrated on Figure 3.3/1. It can grow with the user demand, and provide an early capability at a reduced power level. The satellite/ground receiver pair can be sized to deliver from 1 to 10 GW to the user

The SPS concept is a large disc with a diameter ranging from 3 to 10 Km and includes an array for power transmission. The center of the disc is occupied by a free turning transmitting antenna and feed system, which maintain a continuous Earth-pointing orientation.

The SPS configuration is modular to be adapted to the user need. Its mass, according to the required power, is:

- For 5 GW: 65000 t, among which 42000t for power transmission and 11500 t for power collection
- For 1 GW: 12000 t
- For 0,25 GW: 3000 t

3.3.1 Power generation

A thin film photovoltaic array is mounted on the outer portion of the disc. This portion is rotationally stabilised to be always sun facing. It is a modular system, deployable in units representing a concentric ring of 2-4 m width.

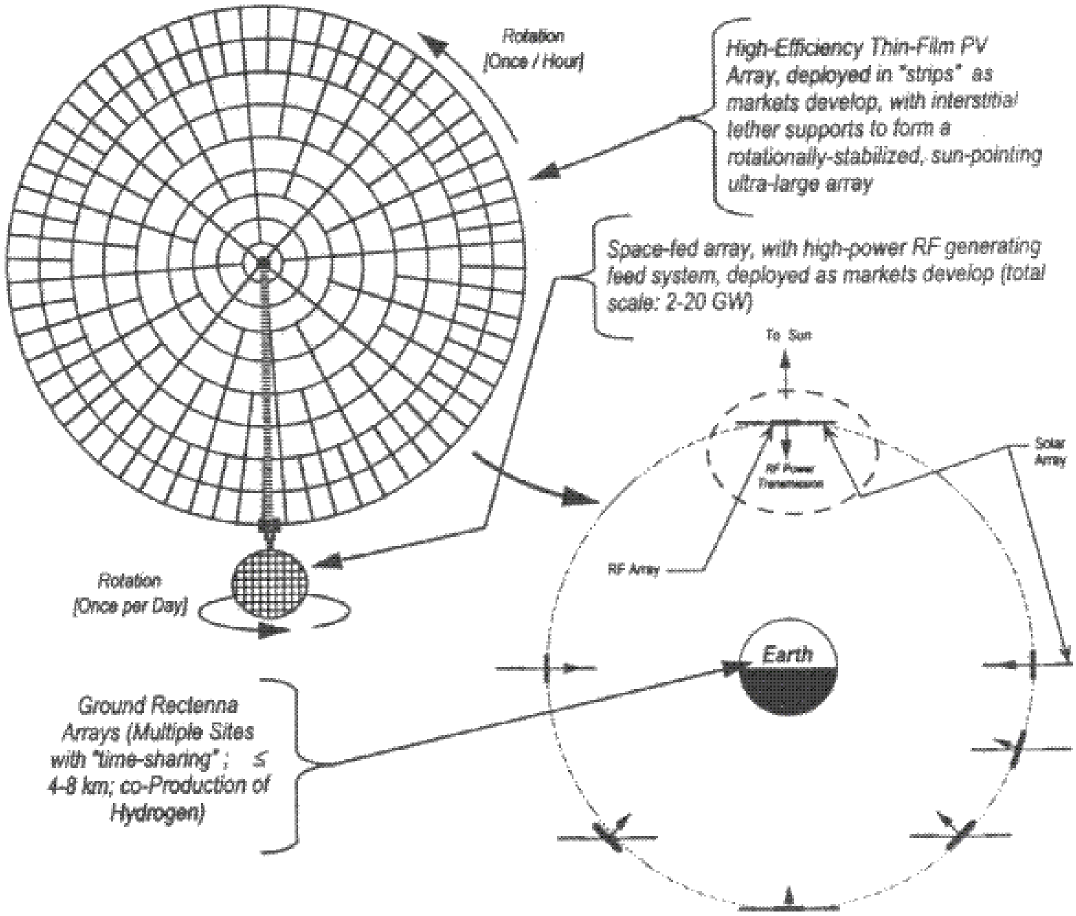


Figure 3.3/1: SolarDisc concept (from NASA Sun Tower concept (NASA Fresh Look study, 1995)

3.3.2 Transmission

The power beam frequency is 5.8 GHz.

Two separate transmitting arrays are used in order to avoid periods of beam blockage by the outer disc. Each transmitting array (element and subassemblies) is about 0.5 to 1.5 Km in diameter (1.27 Km for 5 GW, 0.57 Km for 1 GW), and 1.5 to 3 m in thickness. These arrays are offset from the central axis by about 1 Km. The transmitter feed is located on the central axis and continuously provides power to one of the transmitting array, with a switching to the other transmitter prior to beam blockage by the outer disc.

The transmitter array uses solid state FET devices producing 10 W at 80% efficiency.

The total beam steering capability is 20° (+/-10°).

3.3.3 Receiver

The ground receiver (rectenna array) is a 10 Km diameter site.

3.4 ABACUS REFLECTOR CONCEPT

The Abacus space segment is a two dimensional solar arrays structure (as compared to Sun Tower that is one dimensional). The Figure 3.4/1 illustrates this concept.

This concept keeps the transmitter stationary and the solar arrays always pointing sun, and uses a large rotating reflector to redirect the microwave energy to Earth. The transmission is performed at 5.8 GHz.

That configuration avoids the rotating joint and reduces the electrical cable lengths over those of the Sun Tower concept. Nevertheless, the weight of the cables and the required voltage conversion and power management equipment are a significant part of the satellite mass.

Major concern of this concept is the design of the reflector, which requires a very high surface accuracy.

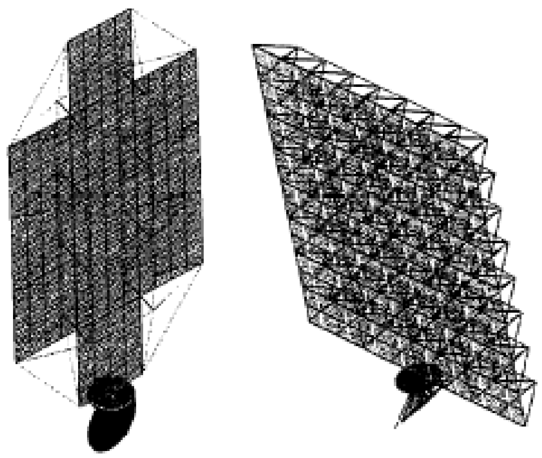


Figure 3.4/1: Abacus Reflector possible configurations (from IAC02-R-1-08 paper)

3.5 INTEGRATED SYMMETRICAL CONCENTRATOR (ISC) CONCEPT

This concept uses two symmetrical clusters of large flat solar reflectors that reflect and concentrate the Sun energy on another structure consisting of two solar arrays surrounding a central transmitter. The solar reflectors always face the Sun. The second structure would rotate so that the transmitter continuously points the Earth. The transmission is done at 5.8 GHz. This concept is illustrated on Figure 3.5/1.

By redirecting the Sun energy close to the transmitter, this concept allows to reduce the length of the cables, then the cabling and PMAD mass.

The temperature expected at the solar arrays present a significant problem for conventional technology. The use of lower concentration would lead to heavier satellite. The lightest concept requires advanced solar arrays and thermal management technology.

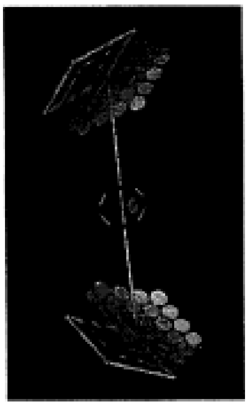


Figure 3.5/1: ISC configuration (from IAC02-R-1-08 paper)

3.6 SUPERSYNCHRONOUS HALO CONCEPT

Information on this concept comes from RD [2].

This concept (space segment part) is illustrated on Figure 3.6/1. The SPS is located on Earth-Sun Lagrangian L2 point, on a halo orbit around this point. The distance between the SPS and the ground site is about 1.5 Million Km.

Due to its position, the SPS has the Sun and the Earth in the same direction: it has a permanent pointing of the Sun and of the ground receiver systems. Thus, it has no rotating part.

It has integrated solar concentrators and microwave transmission dish on one part, and integrated solar cells and solid state transmitter on another part. It is able of 1 GW output power with an assumed transmitter efficiency of 33%. The total mass of the satellite is 1300t.

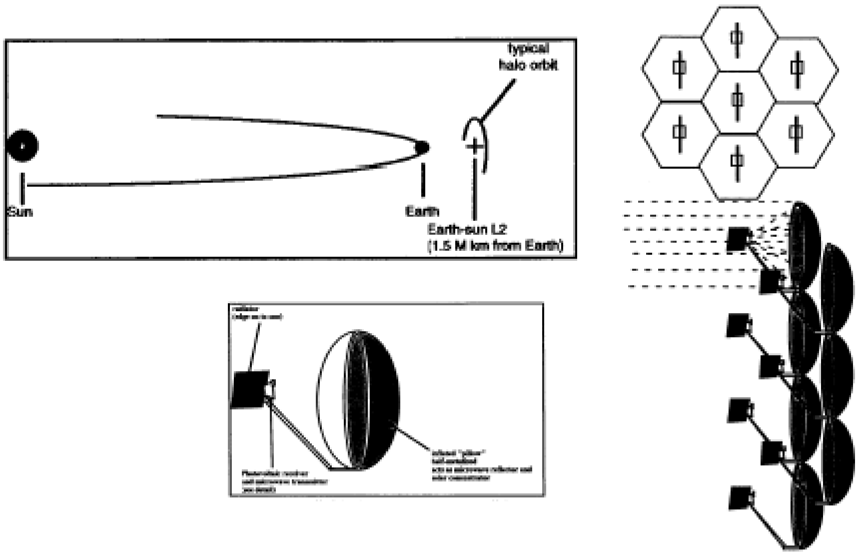


Figure 3.6/1: Supersynchronous Halo concept (from IAC02-R-1-07 paper, RD [2])

The transmission frequency is 30 GHz. The efficiency is lower than at 2.45 GHz, but it allows a much tighter beam.

The solar collector and the transmitting systems include 33000 integrated individual photovoltaic cell/solid state amplifier, and 33000 integrated photovoltaic concentrator/transmitter elements. The efficiency of the concentrator photovoltaic is 35¨%. The solar concentration ratio is 50. The concentrator/transmitter dish is inflatable, with a diameter of 16.5m. The power per dish is 100 kW and a total of 3.3 GW power is generated.

The spot of a single mirror being large at Earth, the beam is narrowed by phasing the 33000individual elements to a phase selected to the rectenna target.

The transmitter diameter is about 3 Km, and the rectenna diameter is about 6 Km.

3.7 EUROPEAN SAIL TOWER CONCEPT

The information on European Sail Tower concept are from RD [4] and [5]

3.7.1 Space segment configuration

The Satellite is located in GEO. Its configuration is derived from the Sun Tower concept. It is gravity gradient stabilised, has a 15 Km length in vertical direction and 0.35 Km width. The satellite mass is 2100t (ref [4]). The satellite is illustrated on Figure 3.7/1.

3.7.2 Power supply

60 pairs of solar arrays (twin module) are mounted along the central truss. The solar arrays are based on thin film solar cells, which are stretched with deployable CFRP masts on each side of the mast. They have 13% of efficiency.

Each single solar cell array has a size of 150m x 150m and a mass of 560 Kg. Each pair produces 7.4 MW of power. The twin module mass is 9t. The power is transmitted from the solar arrays to the antenna via four nitrogen cooled ceramic high temperature superconductors.

3.7.3 Transmission system

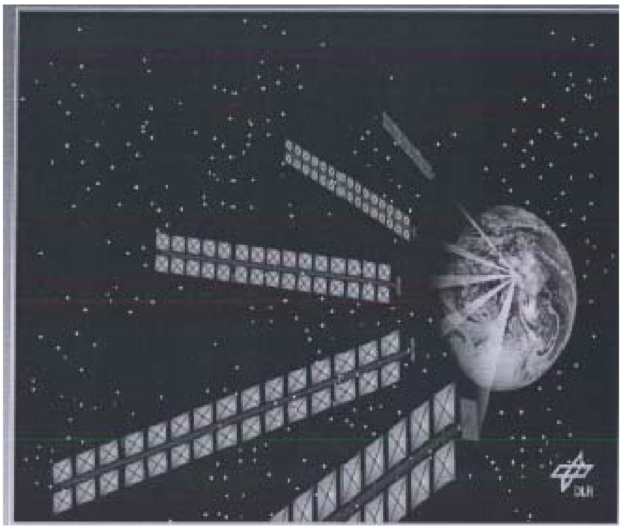
The transmission frequency is 2.45 GHz. The microwave beam is produced by 400 000 magnetrons. The microwave antenna has a diameter of 1000m and a mass of 1600t.

3.7.4 Ground receiver

The ground receiver system is a rectenna that has an efficiency (RF-to-power conversion) of 80% at this frequency. The rectenna size is 11 Km by 14 Km. There are about 100 receiving sites, each covering a safety zone of about 650 Km^2.

3.7.5 Energy

The energy emitted by the solar arrays is 450 MW. The energy emitted by the transmitter antenna is 400 MW. Finally, the power available on ground at the output of the rectenna is 275 MW.



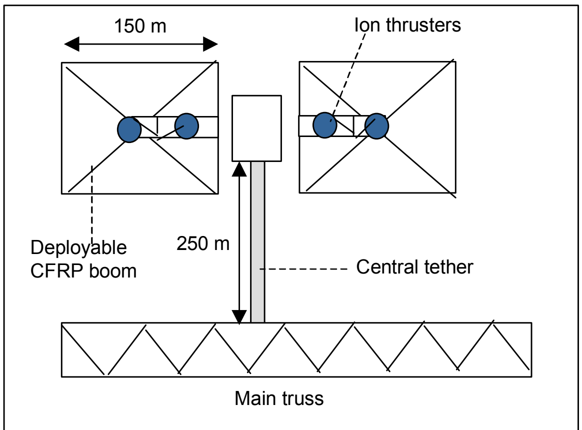


Illustration of twin module (from DLR study)

Figure 3.7/1: Illustration of European Sail Tower concept (from ref [4] & [5])

3.8 SYNTHESIS

3.8.1 Summary of characteristics and performances

The following tables summarize the main characteristics and performances, when available, of each of the reviewed concepts. This table includes the following information:

- The orbital location, the distance to target, the existence of an eclipse on the selected orbit
- Configuration of the satellite (gravity gradient, sun pointing, etc), the type of solar array/reflector (fixed or rotating), the type of antenna (fixed or rotating).
- The power system: configuration of power supply (modular, etc), type of power supply, capability of an element power
- Transmission system: frequency, type of system, conversion
- Beam steering and slew angle
- Power generated and emitted
- Transmitter array size, satellite mass
- Rectenna size

	Sun Tower	Sun Tower	Solar Disc	Solar Disc	Solar Disc
Orbital location	SSO	MEO	GEO	GEO	GEO
Distance to target (Km)	1400 to 2000	6000 to 10000	36000	36000	36000
Eclipse/shadowing	No	Yes	Yes	Yes	Yes
Configuration	Gravity gradient	Gravity gradient	Large disc	Large disc	Large disc
SA/ Reflector	Fixed	TBD	Rotating	Rotating	Rotating
Antenna	fixed	TBD	Fixed to Earth	Fixed to Earth	Fixed to Earth
Power supply	Modular	Modular	Modular	Modular	Modular
Element power (MW)	1.3	1.3			
Type of power supply	Reflector + advanced PV	Reflector + advanced PV	Thin film PV array	Thin film PV array	Thin film PV array
Transmission frequency	5.8 GHz	5.8 GHz	5.8 GHz	5.8 GHz	5.8 GHz
Transmission system	S/ass of elements	S/ass of elements	S/ass of elements	S/ass of elements	S/ass of elements
Power-to-RF conversion	Solid state FET, 10W @ 80% efficiency	Solid state FET, 10W @ 80% efficiency	Solid state FET, 10W @ 80% efficiency	Solid state FET, 10W @ 80% efficiency	Solid state FET, 10W @ 80% efficiency
Beam steering	Electronic	Electronic	Yes	Yes	Yes
Max beam slew	+/- 30°	+/- 30°	+/- 10°	+/- 10°	+/- 10°
Power generated (MW)					
Power emitted (GW)	**0,05**	**0,25**	**5**	**1**	**0,25**
Transmitter array size	**106 m dia**	**260 m dia**	**1.25 Km dia**	**570 m dia**	**280 m dia**
Satellite mass (t)	**530**	**3500**	**65 000**	**12 200**	**3 000**
Rectenna	2 Km	4,5 Km	4 to 8 Km	4 to 8	4 to 8

	Abacus	ISC	Halo	Euro Sail Tower	Sun Tower/ Relay
Orbital location	GEO	GEO	L2 point	GEO	SSO/ Relay in GEO
Distance to target (Km)	36000	36000	1 500 000	36000	35000
Eclipse/shadowing	Yes	Yes	No	Yes	
Configuration	Sun pointing	Sun pointing	Sun/Earth pointing	Gravity gradient	Gravity gradient
SA/ Reflector	Fixed	Fixed	Fixed	TBD	Fixed
Antenna	Rotating reflector	Rotating	Fixed to Earth	TBD	TBD
Power supply	2 dimensional structure	2 Solar reflectors	33000 elements	Modular	Modular
Element power (MW)			100 Kw	7.4	1.3
Type of power supply		Reflector + advanced PV	Concentrator & PV	Thin film solar cells	Reflector + advanced PV
Transmission frequency	5.8 GHz	5.8 GHz	30 GHz	2.45 GHz	5.8 GHz
Transmission system			S/ass of elements Integrated concentrator/transmitter dish of 16.5 m dia	Assembly of twin modules	S/ass of elements
Power-to-RF conversion				Magnetrons (400000)	Solid state FET, 10W @ 80% efficiency
Beam steering	TBD	TBD	No	TBD	Electronic
Max beam slew	TBD	TBD		TBD	+/- 30°
Power generated (GW)			3.3	0,45	
Power emitted (GW)			**1**	**0,4**	**0,25**
Transmitter array size			**3 Km dia**	**1000 m**	**550 m/ Relay 3 Km**
Satellite mass (t)			**1 300**	**2 100**	**19 600**
Rectenna			6 Km	11Km x 14 Km	

3.8.2 Key points for applicability

The applicability of a SPS concept designed for space-to-Earth transmission to the Space-to-space or space-to-planets application is driven by differences in user requirements and mission constraints.

The key issues for this applicability are:

Transmission frequency

- For space-to Earth transmission:
  - the transmission frequency is driven by the atmosphere attenuation, by the transmitter array size and the beam generator efficiency
  - Two frequencies, 2.45 GHz and 5.8 GHz have been considered and are used in the reviewed concepts to minimize the atmosphere attenuation and keep efficiency of the transmitting system. 5.8 GHz was generally preferred in order to reduce the transmitting and receiver antennae size.
- For space-to-space
  - There is no atmosphere in space to space, or space to Moon applications.
  - However, in the Mars case, there an atmosphere attenuation, a priori different from the Earth atmosphere one due to different composition
  - A main driver is to reduce the size of the transmitting antenna, as well as the size of the receiver system. Reducing the size of the SPS transmitting antenna, as well as optimising the overall mass of the SPS will be a stronger constraint than in space-to Earth case, especially if the SPS has to be located in vicinity of Mars, Moon or at Lagrangian point.
  - Laser transmission system is also candidate

Required performances

- For space-to Earth transmission:
  - the power to be delivered at the target (at the output of the receiver/conversion system) is in the range 250 MW to 5 GW.
  - The distance between SPS and target (ground site) is in the range 10000 to 36000 Km.
- For space-to-space
  - the power to be delivered at the target (at the output of the receiver/conversion system) is in the range 1kW to 1MW, that means a ratio of at least 250.
  - The distance between the SPS and the target is in the range 10000 to 50000 Km for mission case 1 and 3, that means same order of magnitude. But, in the mission case 2, it is more than 1 Million Km that means a ratio of at least 20. The only comparable case is

the supersynchronous Halo concept (1.5 Million Km), but it selected a much higher frequency.

Configuration with respect to pointing

The following problems have been identified for the space-to-Earth concepts:

- The solar collector devices are preferably facing permanently the Sun, in particular for technologies like concentrators requiring precise pointing. That avoids also the use of rotating joint with slip rings to transfer power, or a loss of efficiency if the solar collectors remain fixed.
- The antenna array or reflector is preferably oriented towards the target (Earth sites). That requires either beam steering capability, or antenna /reflector rotation.
- The configuration and pointing requirements are linked to the SPS orbital location and attitude

The Space-to-space concept encountered the same problems of solar collectors and antenna pointing. However, in mission cases 1 and 2, the target receiver system is not fixed (as ground sites), so that a slewing of the transmitting beam may be necessary.

Eclipse, shadowing and target visibility

Apart some exceptions (like sunsynchronous orbit), the SPSs in MEO and GEO meet an eclipse period. In that case, they need a power storage on board. It is not clear, according to the concepts, whether they continue to provide power, or if the ground sites have a power storage capability sized for this period.

Another point is the loss of visibility between the SPS and the ground site. That frequency and duration of the loss of contact depend on the SPS orbit. To ensure a permanent power supply, the SPS system includes a constellation of satellites that can solve the eclipse period.

The same problem of eclipse and loss of visibility may exist for space-to-space power transmission, according to the selected orbital location of the SPS. The number of satellites will have to be minimized, in particular for cases where the SPS is not around Earth. Thus, the selection of orbital location will take into account both eclipse and permanent visibility.

Power collection and distribution

A modular approach has been taken for the concept of power collection, in order to allow a growing capability. Most of the concepts use solar concentrator and thin film. A key issue of the reviewed concepts is the cabling length and cabling and PMAD mass. Some concepts aim to reduce this mass.

Same problems for the space-to-space transmission system: the modular approach is favourable, and the reduction of cabling and PMAD mass is a driver. The selection of the technology for the solar collectors may be different.

Transmission system

- For space-to Earth transmission:
    - the beam generator technology used in the reviewed concepts are either a solid state FET 10W, 80% efficiency at 5.8 GHz, or a magnetron tube 5kW, 90% efficiency at 2.45 GHz.
    - The transmitting antenna diameter varies between 260m and 1250m according to the concepts and performances. For SPS in GEO, only the antenna size of 1250m at 5.8 GHz allows to be in the Fresnel zone. The other candidates are beyond this zone (beam dispersion).
- For space-to-space
    - The laser technology is a candidate for the transmission system in most of the applications
    - For RF transmission system, the trend is to use higher frequencies in order to reduce the size of antenna or the dispersion of the beam. In that case, the selection of the beam generator equipment will depend on their performances at this frequency and of the overall system efficiency.

Receiver system

In space-to-Earth concepts, all the receiver systems are using rectennas. There is no size constraint, and large antenna can be deployed on ground sites.

For space-to-space concepts, there is a strong constraint on the receiver system size, which shall not impact the target (satellite, vehicle, rover, etc). Even in the case of large infrastructure on Mars (or Moon), the receiver system will be limited in size (although the constraint would be less severe than on satellites), because it drives the logistic capability to transport to and install it on the planet surface.

Safety rules

The transmission of energy to Earth is constrained by safety regulations, which impose a maximum power density on the Earth surface.

A priori less constraint on space-to-space application. There are impacts on the electrical elements of the target, or compatibility to be ensured with crew on Mars. The critical point would be the spurious lobes.

4 POWER GENERATION OPTIONS

The range of target power consumption associated with the power transmission system efficiency leads to the design of solar collector, conversion into electricity and power distribution able of very high power (100Kw to several MW). To that aim, innovative architectures and technologies have to be identified.

A preliminary review of the sunlight to electricity conversion, of the storage system and of the power distribution (bus voltage) has been done.

4.1 OPTIONS FOR SUNLIGHT TO ELECTRICITY CONVERSION

The conversion of sunlight into electricity can be done by:

- A solar array based on high efficiency cells mounted on a thin film substrate with concentrator or not
- A thermal generator using a Stirling or a Brayton engine

These two options are illustrated on the figures hereunder

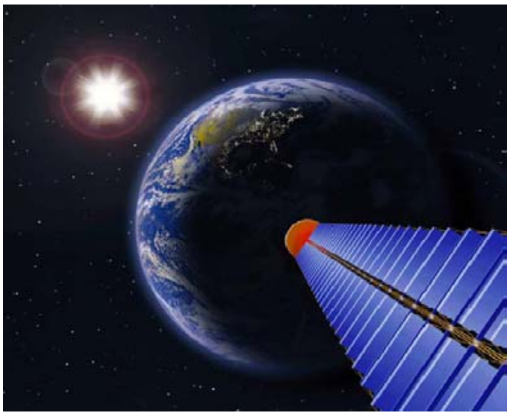


Figure 4.1/1: Example of 1.2 GW solar array (source Boeing GEO Sun Tower) based on thin film solar cells

The Boeing concept can be scaled down from GW to MW.

Figure 4.1/2: Example of 10 kWe thermal generator (Schlaich Bergermann & Partner source)

The Dish-Stirling System is a thermal generator including a parabolic solar concentrator, a solar heat exchanger and a Stirling engine with generator. Global efficiency about 16%.

4.1.1 Solar arrays with concentrators

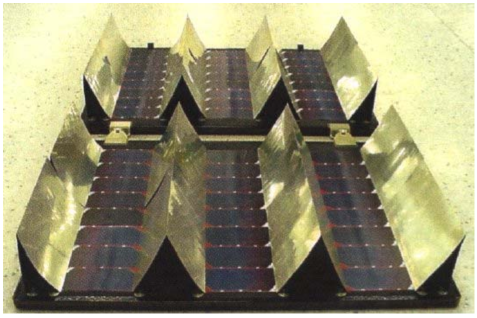
Different types of solar arrays with concentrators may be considered:

- Large reflective concentrators at panel level (as used on the Boeing HS702)
- Small reflective concentrators at cell level (AEC-Able CellSaver patent)

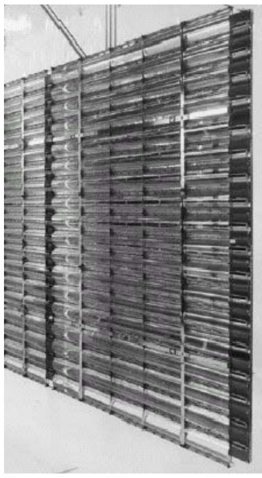
- Fresnel lens (AEC-Able patent).

  The Fresnel lens requires an accurate pointing to Sun (1°), while the concentrators could have a pointing up to 10°. These three types are illustrated on Figure 4.1/3

Large reflective concentrators (used on Boeing HS702)



Small reflective concentrators



Fresnel lens

Figure 4.1/3: Illustration of possible types of solar arrays with concentrator

4.1.2 Performances of the options for sunlight to electricity conversion

The main assumed performances of the sunlight to electricity conversion are summarized in the hereunder table, where:

- The efficiency is the ratio between the usable electrical power and the collected sun power
- The density is the ratio between the mass and the collected sun area
- The solar arrays are based on triple-junction solar cells, and on a thin film
- The thermal generator cost is based on terrestrial value times 10 for Space application

		Solar Array				Thermal generator (Stirling or Brayton cycles)
		Planar	Large concentrators	Small concentrators	Fresnel Lens	
Present	EOL Efficiency	22%	20%	21%	19%	25%
	Density (kg/m²)	2.2	2.7	2.9	1.8	79
	Cost (k€/m²)	225	170	170	200	30
2030 Time frame	EOL Efficiency	30%	27%	29%	25%	35%
	Density (kg/m²)	1.5	1.7	1.7	1.8	5
	Cost (k€/m²)	225	170	170	200	30

The figure 4.1/4 gives the total cost per delivered watt of each option as function of the launch cost per Kg:

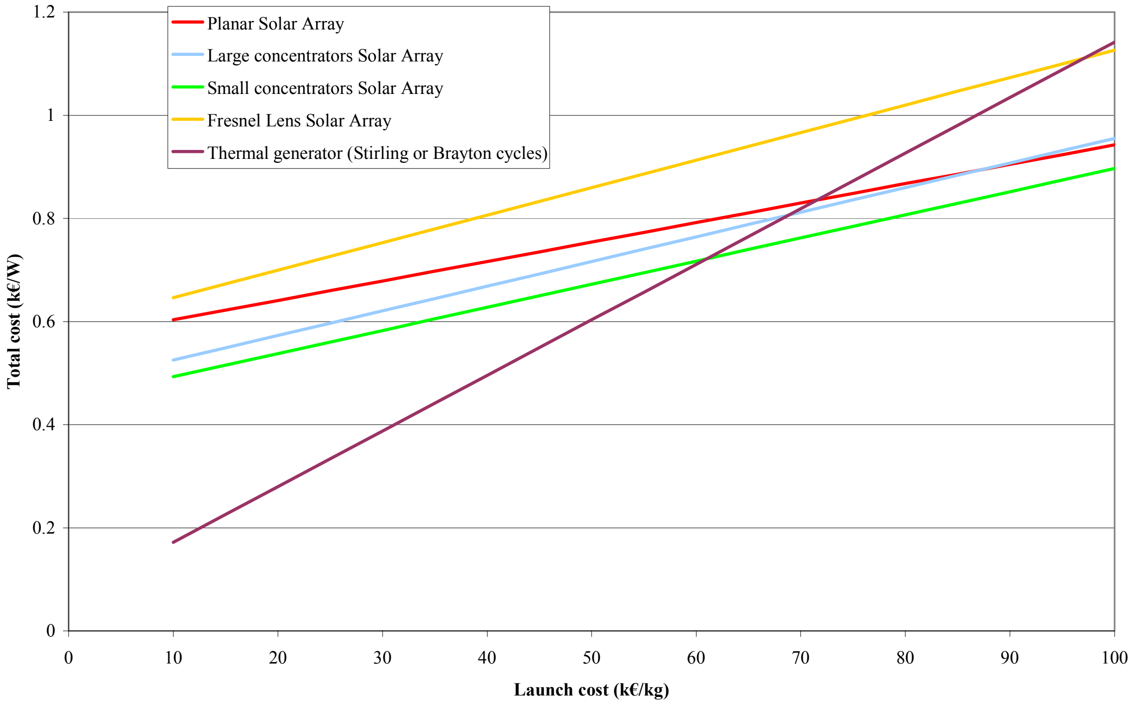


Figure 4.1/4: comparison of the options for the sunlight to electricity conversion

As preliminary conclusions:

- The Fresnel lens solar arrays seem the less interesting option
- The small concentrator are more interesting than the large concentrator
- The planar technology is attractive if the launch cost is higher than 165 k€/kg. Therefore, it is not retained.
- The thermal generator appears very attractive, but the assumptions need to be confirmed.

Therefore, the small concentrator and the thermal generator are the preferred options.

4.2 STORAGE TECHNOLOGIES

Three types of storage technology have been reviewed. This review has been done for the case where the SPS has to provide power to the target including during eclipse. If it is not the assumption, the SPS platform itself will require only a low power during this phase, and such low power have not been considered in the assessment. The three power storage technologies are the Li-ion battery, the regenerative fuel cells and the energy storage wheels. Their assumed performances are summarized in the table hereunder, which indicates the current performances as well as the performances expected in the future (2030 timeframe).

In this table, a mass offset of 100 Kg has been taken for the regenerative fuel cells, and the Energy Storage Wheels density assumes the use of nano carbon fiber technologies.

		Li-Ion battery	Regenerative Fuel Cell	Energy Storage Wheel
Present	Round-trip efficiency	95%	40%	95%
	Density (Wh/kg)	120	400	500
	Cost (€/W or €/Wh)	10	20	
2030 Time frame	Round-trip efficiency	95%	40%	98%
	Density (Wh/kg)	150	600	1000
	Cost (€/W or €/Wh)			

4.3 POWER DISTRIBUTION

A very high power has to be supplied, and it shall be supplied preferably on High Voltage Bus. Indeed, to provide 2 MW under 1000 V leads to a current of 2000 A. This is manageable, as an application of 1600 A has already been studied. It should be manageable up to 3000 A. It is proposed to limit the current at 3000 A (with a minimum bus voltage of 100 V) and then the voltage to 1000 V.

However, a high bus voltage leads to EEE parts availability problems.

For such high current, the harness shall be based on Aluminium bus. This is a conclusion of the High Power Satellite Platform study for ESA.

Finally, the interest for an AC power bus is questionable.

4.4 MISSION CASES

The two preferred options (small concentrator and thermal generator) have been assessed for three mission cases:

- Earth LEO orbit with no eclipse (HNA 18h, altitude higher than 1400 Km) or Lagrangian point L4. The minimum solar flux is 1326 W/m^2
- Earth GEO orbit: 72 min eclipse, and minimum solar flux of 1326 W/m^2
- Mars GEO orbit: 79 min eclipse, and minimum solar flux of 490 W/m^2

An end-to-end efficiency of 10% has been assumed for primary and secondary sources sizing.

4.4.1 Mission case: Earth LEO or Lagrangian point

The figure 4.4/1 and 4.4/2 show respectively the mass of the sources and harness, and the cost of the sources as function of the target power requirement for the two options.

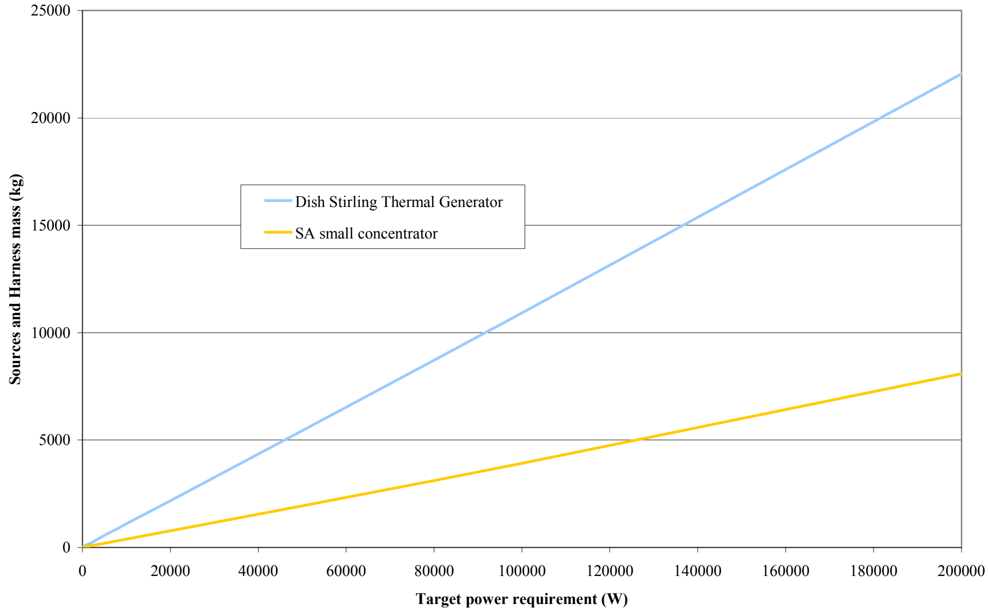


Figure 4.4/1: Mass of the sources and harness as function of target power requirement in the case of no eclipse

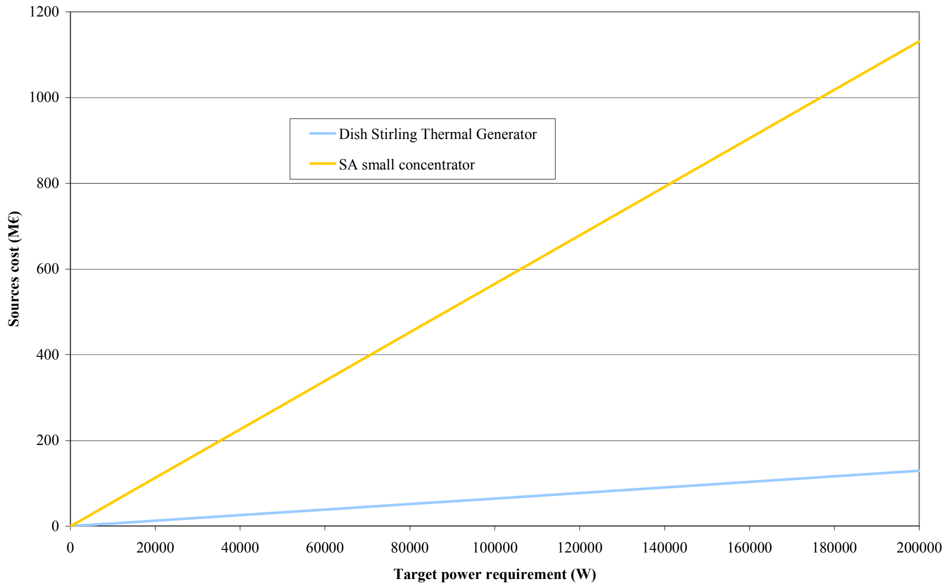


Figure 4.4/2: Cost of the sources as function of target power requirement in the case of no eclipse

4.4.2 Mission case: Earth GEO

The figures 4.4/3 and 4.4/4 show respectively the mass of the sources and harness, and the cost of the sources as function of the target power requirement for different pairs of energy collection/conversion system and storage system.

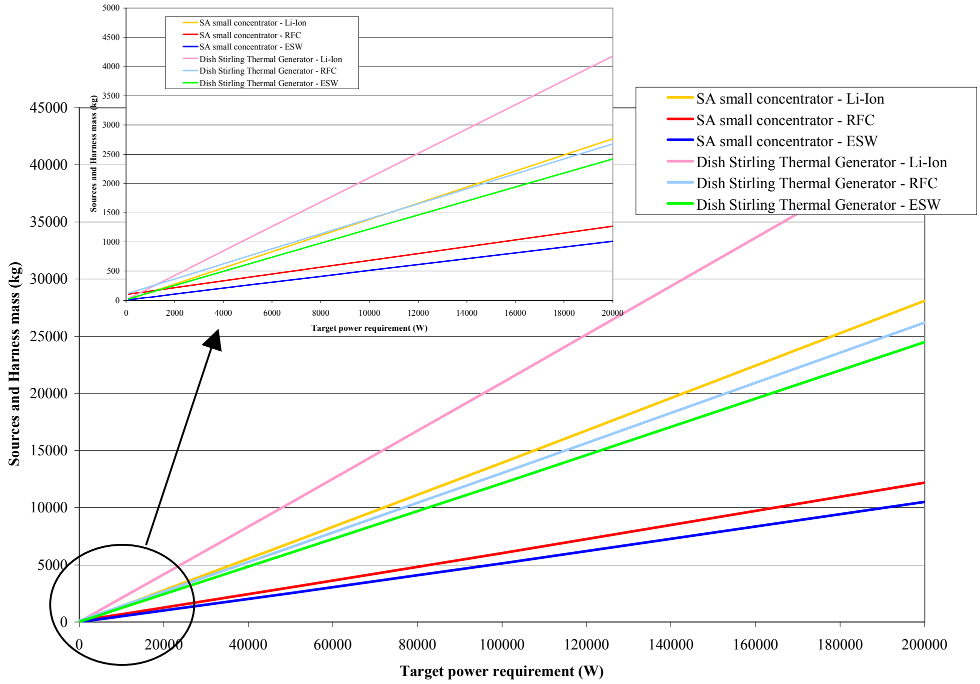


Figure 4.4/3: Mass of the sources and harness as function of target power requirement in the case of SPS in Earth GEO orbit

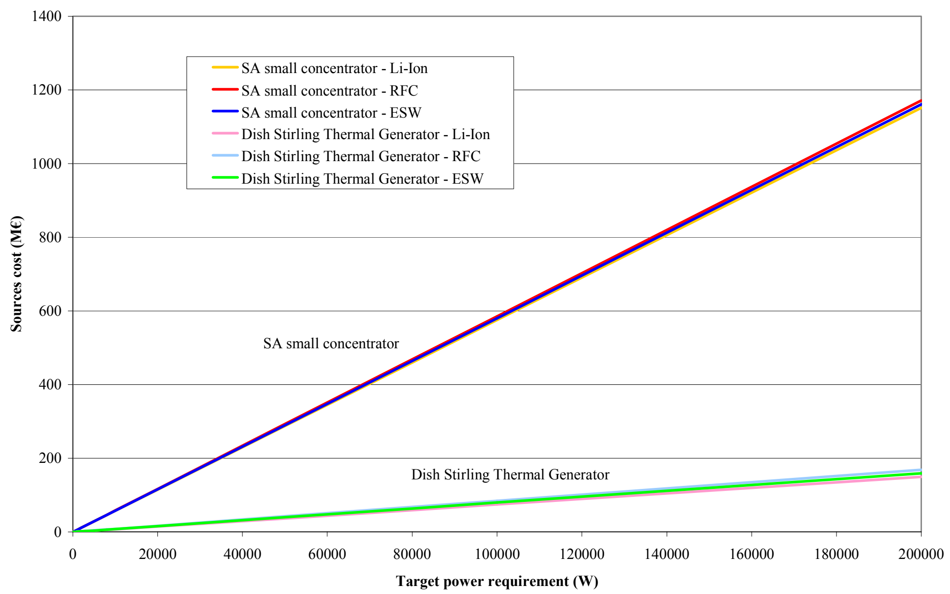


Figure 4.4/4: Cost of the sources as function of target power requirement in case of SPS in Earth GEO

4.4.3 Mission case: Mars GEO

The figures 4.4/5 and 4.4/6 show respectively the mass of the sources and harness, and the cost of the sources as function of the target power requirement for different pairs of energy collection/conversion system and storage system.

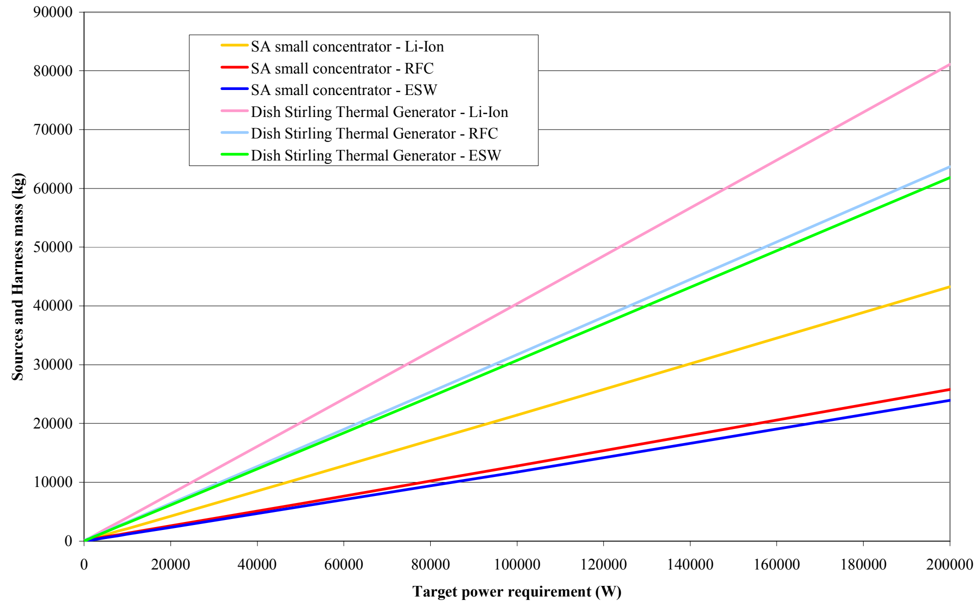


Figure 4.4/5: Mass of the sources and harness as function of target power requirement in the case of SPS in Mars GEO orbit

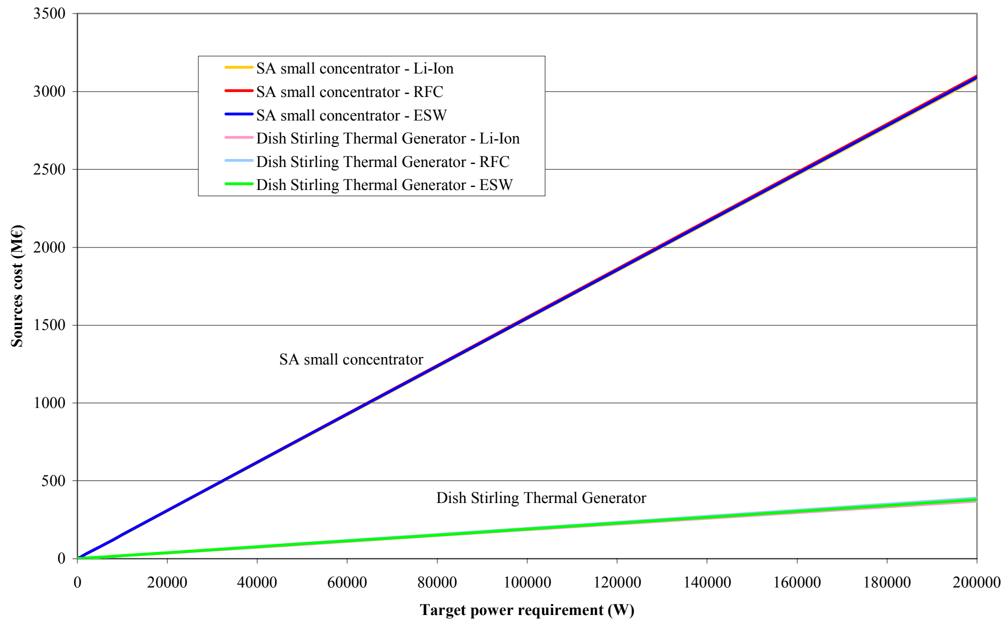


Figure 4.4/6: Cost of the sources as function of target power requirement in case of SPS in Mars GEO

4.4.4 Preliminary conclusions

This preliminary evaluation leads to the following conclusions:

- For the Earth LEO case, where no eclipse is considered, the solar array small concentrator appear more attractive than the Stirling system on the mass point of view (figure 4.4/1), while on the cost point of view (figure 4.4/2), it is the Stirling system which seems the most attractive.
- For Earth or Mars GEO cases, the solar array small concentrator coupled with Energy Storage Wheels is the most attractive solution on mass point of view while, on cost point of view, the Stirling system remains more interesting.
- For the assessment, the launch cost has to be considered
- High development efforts have to be done on Stirling system, regenerative fuel cells and energy storage wheels. The effort on the storage technologies is necessary if the SPS has to provide power to the target also during the eclipse phase.

The table hereunder summarizes for both primary and secondary sources the development status, the development risk and timeframe, and the advantages and drawbacks.

	Primary Sources		Secondary Sources		
	SA small concentrators, Thin film, TJ cells	Stirling Engine	Li-Ion	Regenerative Fuel Cell	Energy Storage Wheels
Development Status	Partly developed by AEC-Able To be developed in Europe	Developed in Germany for terrestrial application	Space qualified up to ~20 kW	European products available for terrestrial application To be developed for Space application	Studies have started since 1999 in ESA Nano Carbon Fibre to be developed
Development Risk & Time frame	Medium ~5 years	High ~10 years	Low ~1 year for > 20 kW	High ~10 years	High ~10 years
Advantages	Lower mass	Cost	Cost	Mass	Mass, Lifetime
Drawbacks	Cost	Mass, moving elements, Lifetime, Pointing reqt.	Mass	Cost, Lifetime	Cost, interaction with AOCS

5 LASER POWER TRANSMISSION SYSTEM

5.1 LASER POWER CONVERSION APPROACHES

Several parameters are driving the design of the

Laser Space Power transportation concept.

The most important is closely linked to the receiver power generation system. Two different power generation processes can be envisaged:

- Photovoltaic solar cells:

  The Solar cell is usually designed for a maximum power conversion efficiency in the range of the maximum solar emitted power .In consequence the emitted laser wavelength has to be in the visible spectral range :λ =0.35-1 µm (so called visible laser system)

- Thermal Power generation

  It would be also possible to produce useable energy thanks a thermal power plant. This approach is less currently developed than the previous one but it is efficient enough to be considered for future Space missions In that case the Emitted laser wavelength has to be the thermal spectral range: λ=5-12 µm (IR laser system)

The second driving parameter is the obviously the distance between the laser emitter and the receiver. As an example the scaling factor between 30000 km and 1.5 million km is 2500. This parameter is directly impacting the level of the required emitted laser power, as the received power density is decreasing with the square of the distance.

For trading the laser system itself the inner efficiency of the generation of the laser energy has to be taken into account. In space environment the Solar radiation is the only available power source. So, the overall efficiency, Emitted laser radiation/Solar radiation, is an important trade-off parameter. This efficiency is mainly related with the optical pumping mechanism (physical process which generates the optical amplification capability of the laser material). Two different approaches will be proposed

- Direct Solar pumped laser
- Laser pumping process based on primary electrical power

The later being the most straightforward and currently used in scientific space application.

Finally, the optical design of the optical emitting “ antenna” (telescope) will drive the optical beam divergence. To transmit optical power over large distance we shall generate narrow divergence optical. In consequence we must manufacture large pupil telescopes. Two concepts are candidate

- Large single telescope associated with a powerful embarked on a satellite. Several satellites can point the same area to increase the received power density at receptor level.
- A constellation of relatively small satellites that embark moderate power laser. The lasers are optically phased. The constellation constitutes a laser phased array emitting in the same direction.

After analysing these two optical configurations we will review the laser candidate in both visible and IR wavelength range.

5.2 NON-COHERENT LASER CONSTELLATION

It is the straightforward approach.

One satellite embarks a laser system; the satellite individual control points the receiver area with a diffracted limited beam. This concept is currently proposed by the US Defence program " Space Based Laser"(SBL)

A constellation of Space laser satellite can be imagined in order to increase the received power area density. The total received power is the addition of the individual received power. (as shown figure 5.2/1)

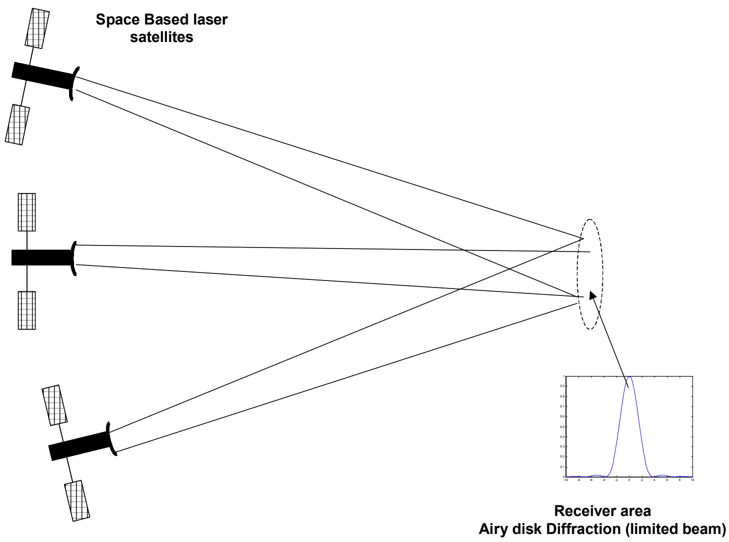


Figure 5.2/1 : Non Coherent laser Constellation

The received power is concentrated in the a Airy Spot which is related with the aperture size of the emitting telescope; There is a simple relation between the size of the optics and the emitted laser power which the most important parameter for selecting the laser system. The merit function that characterizes the laser system is $P\Phi^2$

$$P.\phi^2 = (\pi/4)\,(1/N).E.D^2.\lambda^2$$

P is optical power

λ is the laser wavelength

D is the distance between receiver and laser

Φ is the diameter of the optics

E is the illumination in w /m² at the receiver level

N is the number of satellites

Several critical items have been identified. There is no huge technological step between the currently developed technology and the requirement of optical concept. We have only to push the present technologies up to their limits.

- The diameter of the emitting optics

The emitted power is inversely proportional to the square of the telescope diameter. The largest telescope that is presently under development is the 6m IR telescope proposed for the James Webb Space Telescope mission. (JWST) (Figure N°5.2/2). The main technical feature is the segmented primary mirror approach. Individual hexagonal segments that are individually and precisely aligned thanks to reference stars compose the large primary mirror. Using the same segmented mirror technology, we can envisage 30 m telescope diameter for laser emission. The alignment could be easier than JWST one because the field of view of laser emitting system is narrower than imaging system as JWST. Such parameter relaxes the Optical quality constraint; the main size limitation will be the integration constraint in orbit. (Transportation and precise alignment mechanism).

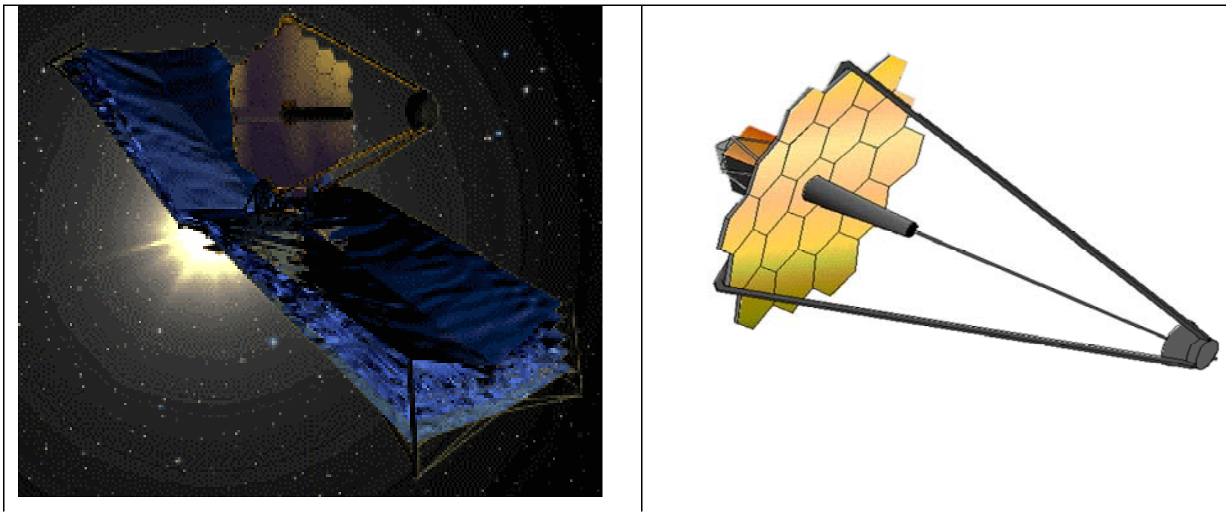


Figure 5.2/2: JWST Telescope (from NASA [1])

- Pointing accuracy: in the range of tens of nano-radiant

The pointing accuracy is one order of magnitude lower than SILEX experiment (demonstrated in orbit). It will be difficult to maintain large optics (several meters) in such accuracy range. New pointing mechanism with frictionless bearing (magnetic or other) has to be developed.

[1] NASA JWST Home page

5.3 SPACE BASED LASER ARRAYS

This approach is based upon a combination of two lasers applications, which were demonstrated on ground

- Seeding a High power laser (Slave) by a stable and frequency controlled low power laser (master in order to force the slave laser to emit on the same frequency than the master laser
- The phase of the emitting beam of each slave laser is controlled to ensure a common phase at the output aperture of each individual laser. (Figure N°5.3/1) The emitted beam is diffracted by the very large array and concentrates the flux in a very small spot.
- This application was experimentally demonstrated in Europe for Optical communication application and in USA for Laser weapon applications.

The satellite constellation is composed by several tens of high power slave lasers which relative positions are perfectly controlled within a few mm (formation flying). A "low power" master laser is seeding each slave lasers. The frequency control is realised by the master laser satellite. Optical delay lines embarked in the slave satellites will ensure this phase control. A beacon signal has to be provided by the receiver or by a guide star

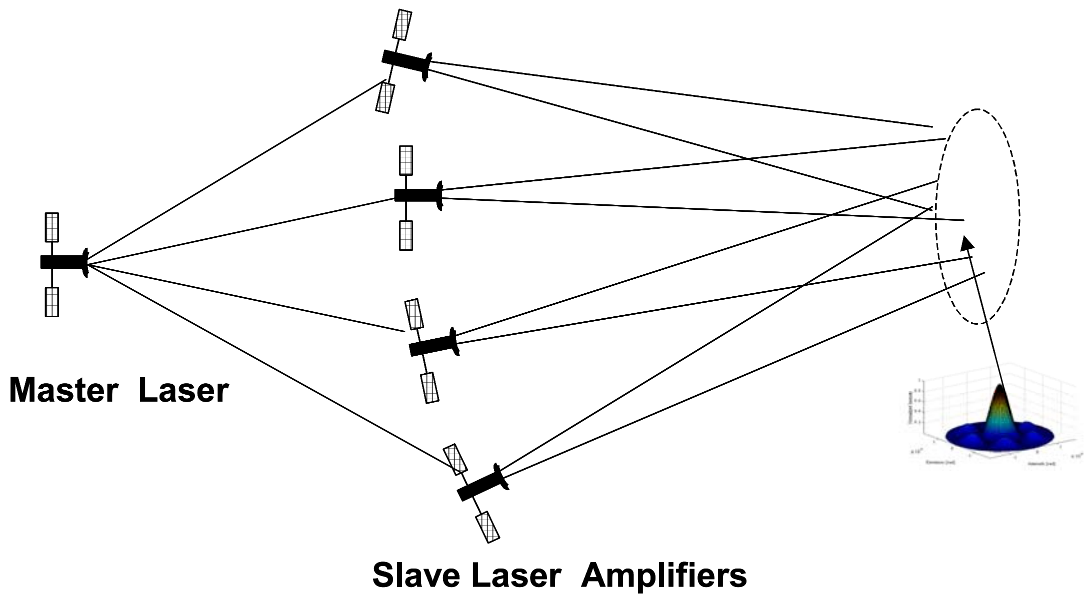


Figure 5.3/1: Phased laser arrays

A constellation of Laser satellites can offer the following advantages

- High CW power due to a large number of individual lasers
- Low divergence due the large phased emitting area
- Beam steering capability by introducing phase differences between each slave lasers

The power density at the receiver level can substantially be increased in comparison with a non coherent laser constellation with equivalent total emitted power and the same number of satellite (Figure 5.3/2)

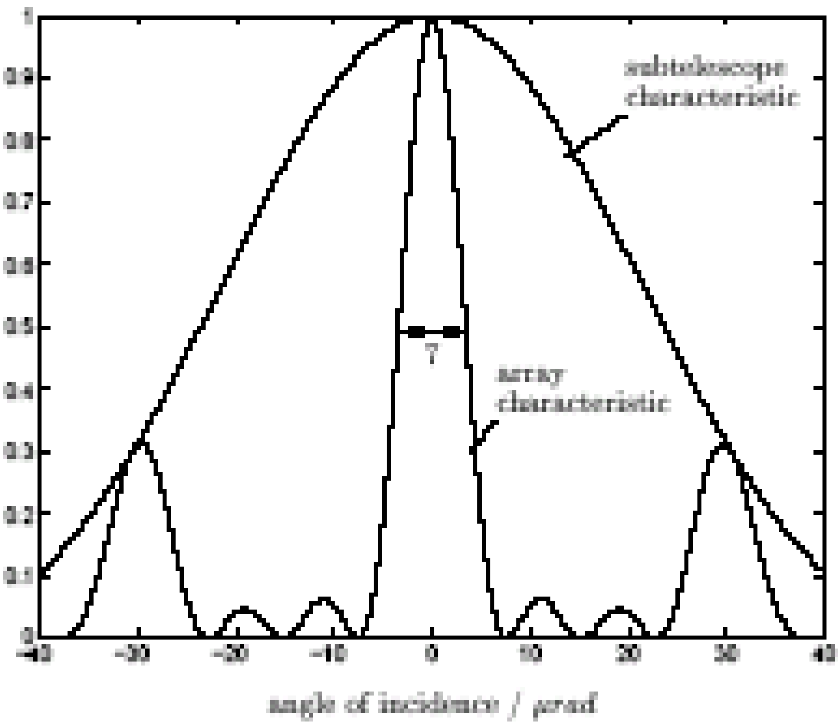


Figure 5.3/2: Far field pattern of a phased laser array with 16 emitters

The Formation flying control is similar to the formation flying that is presently studied for DARWIN and TPF (Terrestrial Planet Finder program)

- Relative low accuracy intersatellite distance (in the range of 10µm) and attitude control
- The phase control is performed directly on the Slave beam by optical means (a few nm)
- The optical element of the constellation is aligned and phased on receiver beacon or guide star

An artiste view of the hyper telescope proposed in TPF program is sketched in figure 5.3/3. The light is reflected onto a central focal plane located in satellite hub by several mirrors embarked in independent satellites, which intersatellite distance, is precisely controlled.

Figure 5.3/3: TPF Hyper telescope configuration (from [2])

5.4 NUMERICAL ASSESSMENTS OF LASER POWER SYSTEM

In this chapter we briefly give several numerical assessments to assess the main parameters of a future SPS system. Two cases were analysed

- Distance between Laser emitter and receiver: 30000 km
- Distance between Laser emitter and receiver: 1.5 M km

Two working hypothesis were taken:

- λ= 532 nm (frequency doubled 1.064 µm)
- Optical illumination at receiver level: 1000 W/m²

5.4.1 Mission N° 1: distance between Laser emitter and receiver: 30000 km

The main parameters of the SPS system are depicted in the following table.

[2] Terrestrial Planet finder: Mission architecture Study reports-NASA-The BOEING SVS- team products for TPF Architecture product contract March 2002

Laser system parameters	
Laser power	3 K watt
Operating Wavelength	532 nm
Telescope Diameter	10 m
operating distance	30000 km
Diameter of the Spot on target aera	1,9 m
50% Loss pointing Accuracy	**32** nrad
Surface of the PV target area	**1** m²
Efficiency of the PV Cell	50 %
Illumination at target level	1,01 kW/m²
Generated electrical power	0,5 kW

Table 5.5/1: SPS system parameters for 30000 km intersatellite distance

Only one single satellite with 10 m optical telescope was considered, leading to 3 KW output power laser. These two driving parameters seem achievable with currently on going technology.

5.4.2 Mission N° 2: distance between Laser emitter and receiver: 1500000 km

Two different configurations were analysed:

- One satellite with a large telescope
- A constellation of 5 satellites with phased laser arrays

The results are depicted in tables 5.3/2 and 5.3/3

Laser system parameters	
Laser power	800 K watt
Operating Wavelength	532 nm
Telescope Diameter	30 m
operating distance	1500000 km
Diameter of the Spot on target aera	32,5 m
50% Loss pointing Accuracy	**11** nrad
Surface of the PV target area	**1** m²
Efficiency of the PV Cell	50 %
Illumination at target level	0,97 kW/m²
Generated electrical power	0,5 kW

Table 5.5/2: SPS system parameters for 150000 km intersatellite distance with one satellite

Laser system parameters	
Laser power	200 K watt
Number of slave laser	5
Operating Wavelength	532 nm
Array dimension	50 m
operating distance	1500000 km
Diameter of the Spot on target aera	19,5 m
Array efficiency	30,0 %
50% Loss pointing Accuracy	**6** nrad
Surface of the PV target area	**1** m²
Efficiency of the PV Cell	50 %
Illumination at target level	1,01 kW/m²
Generated electrical power	0,5 kW

Table 5.5/3: SPS system parameters for 1.5M km intersatellite distance with 5 satellites constellation

For these applications it clearly appears that the laser out put power is in the range of several hundreds of KW CW power. This is a challenging development for space application. The feasibility of such lasers is far to be demonstrated

The gain of the constellation over a single satellite is interesting but did not provide any technological step for the laser. We are still in the range of hundreds of KW. This is due to the estimated efficiency of the beam phasing

This preliminary assessment shows that the distance is a key element of the feasibility of laser SPS system

For long distance, very large lasers (equivalent to the champion laser developed on ground) have to be developed. In the next paragraphs we will look on after of such huge scientific lasers.

5.5 REVIEW OF VISIBLE LASER TECHNOLOGY

5.5.1 EXCIMERE lasers

It is a Molecular Gas Laser. Exciter stands for excited dimmer, a diatomic molecule usually of an inert gas atom and a halide atom, which are bound in excited states only. These diatomic molecules have very short lifetimes and dissociate releasing the excitation energy through UV photons

The most current lasers are UV laser

- ArF: λ=193 nm
- KrF: λ=248 nm

This type of laser is often used in pulsed mode, and cannot deliver very high CW power. The power efficiency of excimere lasers is typically about 10%, (could be better for KrF). The Lifetime is relatively short for space application

This type of laser is not considered as a potential laser candidate

5.5.2 Laser diodes

This laser is the most efficient laser (up to 80% plug-in efficiency) .The emitted wavelength of the AlGaAs is in the range of 795-850 nm: that is precisely in the optimum wavelength range of solar cell quantum efficiency. But presently, the most important technological effort is made for diode that are emitting in the range of 950 nm (for pumping of 1.55µm fiber laser). A new development for AlGaAs laser can be easily derived from this later technology but it has to be entirely supported by the SPS program

Large area emitting system has been developed, made with thousand individual diode stripes and the technology could be scaled up to larger area (Figures 5.5.2/1)

Most of these stacks are not coherently phased It is theoretical possible pour realise such large coherent surface. In the early 90's, several coherent stacks were developed at laboratory level. The main limitation is the thermal control of such diode panel in order to maintain the optical coherence between each individual stripes. This approach for producing high power laser diode is no longer considered. Fiber laser with laser diode pumping offer better solution

Laser diode could be considered as a very interesting candidate, at least for optically pumping solid state laser

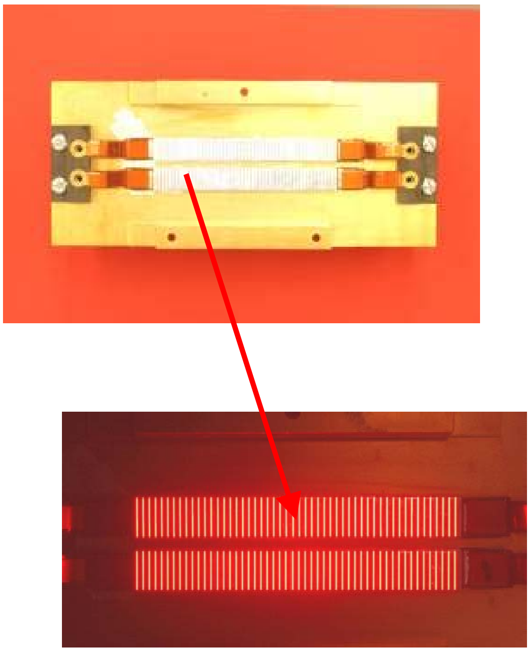


Figure 5.5.2/1: 1KW laser diode stack (the length of the Stack is 11 cm) (from Laser Diode Inc [3])

5.5.3 SOLID STATE laser

These lasers are based on crystal technology and they widely used for industrial and scientific applications

The active medium is excited ion embedded in crystalline matrix. All the lasers are optically pumped in the visible range (in particular an pumping process based on solar radiation can be considered). The current solid-state laser technology is:

- ·Nd: YAG (Better homogeneity of dopant)
- ·Nd: Y2O3 (Lower fabrication cost)
- ·Cr2+: ZnSe (Possible tailoring of dn/dT)
- ·Nd: Y3ScxAl (5-x) O12 (crystal growth still possible)
- ·Sapphire: Ti (tuneable wavelength around from 0.6 to 1μm)
- ·Ruby (emitted wavelength λ= 694 nm)

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[3] Laser Diode Inc Web Page

These lasers, in particular Nd based laser, can be easily pumped by laser diode

Solid-state lasers are interesting candidates for Power Space Transportation

Nd: Yag Laser

They are the most widely used laser for both Space and ground application. The emitted wavelength is λ= 1064 nm. They are efficiently pumped by laser diode or Solar radiation (several experiment are presently on going). Pure Visible radiation λ= 532 nm can be efficiently emitted (100% efficiency with doubling device in the lasing cavity).

Long coherence CW length emission can be obtained (narrow frequency bandwidth).

The overall plug in efficiency for laser diode pumped system is about 15 % (Figure 5.5.3/1)

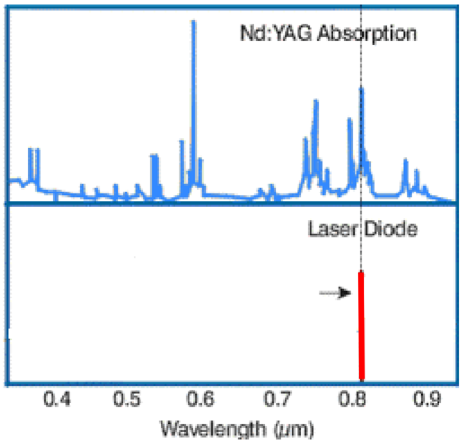
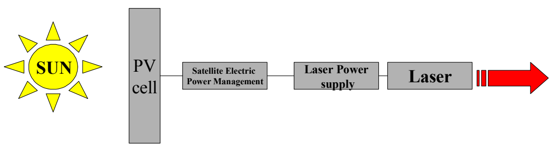


Figure 5.5.3/1: The adequacy of the laser diode radiation with the Nd: Yag absorption band favours the plug-in efficiency of this laser.

For a solar pumped system a careful detailed calculation is to be made for establishing the overall efficiency, and to compare it to a more classical concept based on PV solar cell and laser diode pumping.



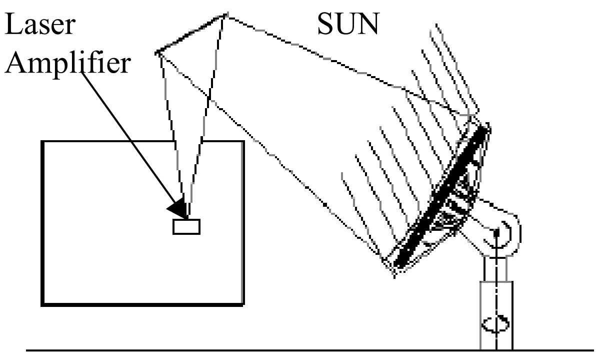


Figure 5.5.3/2: Two Nd: Yag laser pumping configurations are proposed for SPS applications: classical concept with PV solar cell and diode laser pumping and direct solar pumping

Huge Nd: Yag lasers have been built for several scientific and military applications: Laser Mega-joule in France (Figure 5.5.3/3), Nova laser at Lawrence Livermore National Laboratory in US

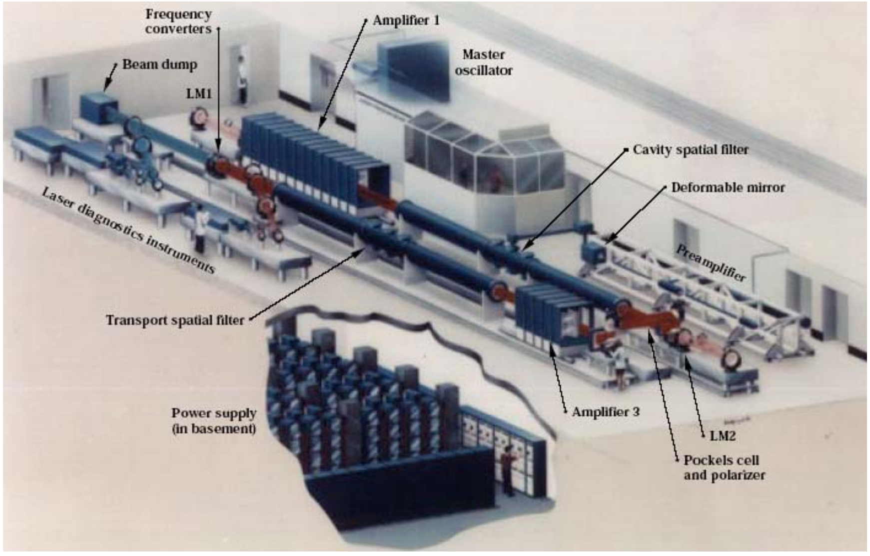


Figure 5.5.3/3: Experimental Part (LIL) of the Laser Mega Joule (*CEA courtesy)*

In consequence the experience of huge laser plant operation exists on ground

- Thermal control
- Surface laser damage
- Frequency control

This experience could be the basis for developing the Space Power Transportation Laser. But the maintenance of such laser in space will require large facility as ISS or larger.

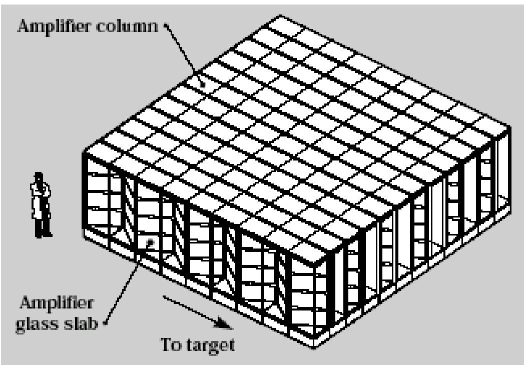


Figure 5.5.3/4: Amplification area of large Nd: Yag laser (maintenance and replacement of slab amplifier) (CEA courtesy)

Future Trends

Several parameters are to be improved

- Optical pumping efficiency (for both Solar and laser diode approaches)
- Power handling for compactness
- Thermal control

Different approaches are proposed for developing huge laser in space. Most of them are based on the direct solar pumping which seems the most attractive (theoretically the most efficiency).

The recent development of Hollow fiber offers new flexible solutions for an efficient solar power conversion in laser radiation .The solar pumped volume can be located at the focal area of a solar concentrator (axicon). The coupling efficiency is the optimum. The active material can be embedded in the hollow fiber and constitute a fiber laser. Due to long interaction with solar radiation high power can be generated. This energy can be routed by passive hollow fibers towards emitting antennas.

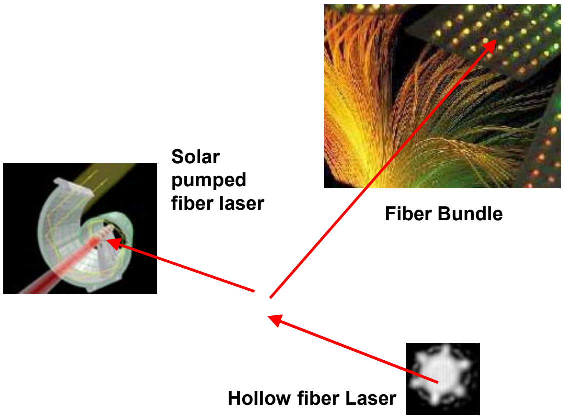


Figure 5.5.3/5: Solar pumped Hollow fiber laser (from L Di Domenico [4])

A bulk approach was proposed for power beaming in the near earth space. The laser satellites are located in sun synchronous orbit. That provides a mean of continuous pumping the gain region of the laser by sunlight that always arrives from the same direction. The concentration of the sunlight achievable is 45000 times the intensity of the naturally occurring light. The laser material is thermally controlled down 100K the low temperature; the optimum choice of materials and the optimum gain medium power access to conditions needed for power beaming.

The laser is formed from a series of modular elements arranged in a long row (Figure 5.5.3/6)

[4] L Di Domenico-Power Beaming Technology Quaterly Review August 2002

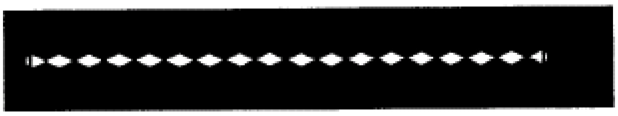


Figure 5.5.3/6: Laser gain region. The laser beam is the lowest order gaussian mode extending through all the gain elements

The modular structure facilitates robotic construction. Megawatt can be accessed with about 50 modules of about 10- 50 KW each. The length of each element is about of 2 km. The mode diameter is 3cm.The cooling of amplifier material is essential. The gain element is constructed to facilitate removal of waste heat while providing adequate gain to support laser action under the pumping provided by the sunlight (Figure 5.5.3/7)

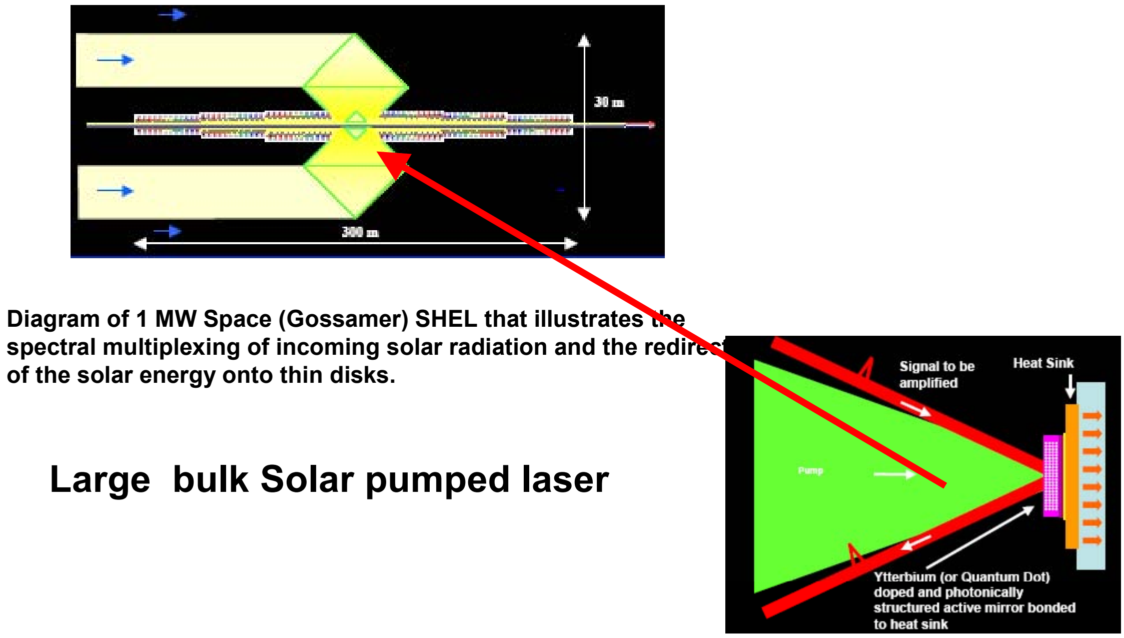


Figure 5.5.3/7: Large solar bulk laser configuration .A particular attention has to be paid for the thermal control of the optical gain medium (from [5])

5.6 REVIEW OF IR LASERS

5.6.1 Chemical lasers

These lasers are mainly developed for military applications and laser weapons (Space Based Laser**).** Several types of lasers were developed

[5] Laser for Power Beaming R .Fork 2002

- **HF laser:** "This chemical laser combines heated hydrogen (produced in a combustion chamber similar to the one in a rocket engine) with fluorine gas to produce excited hydrogen fluoride molecules. The laser that results radiates on multiple lines between 2.7 µm and 2.9 µm. Several Mw in a few seconds can be delivered. The mass of this type of laser is relatively high (40T) and the consumption of chemical compounds is very high (20 T for 40 shots of 3 s duration)
- **HF overtone laser:** Optical coatings on the HF laser can suppress the fundamental HF wavelengths and cause lasing at roughly 1.3 µm. This is in the experimental stage, however promising results with BMDO's Alpha laser show 65% efficiency at low powers. This in effect is a system gain since the laser brightness is proportional to the square of the inverse of the laser frequency.
- **DF laser:** "The deuterium fluoride laser is chemically the same as the HF laser. However, the increased mass of heavy hydrogen, deuterium, shifts the laser wavelengths to between 3.5 µm and 4.0 µm.

- **COIL laser:** "In the chemical oxygen iodine laser (COIL) … excited atomic iodine is used as the lasing medium. The first step involves blowing chlorine gas past a basic hydrogen peroxide solution. Chlorine migrates into the liquid and reacts to produce excited oxygen molecules. Excited oxygen then escapes from the solution and is mixed downstream with molecular iodine. The iodine molecules are broken up and individual atoms are excited by a nearly resonant reaction with the oxygen in multiple reactions. This last transfer of energy leaves atomic iodine in an inverted population, and this takes place between the mirrors of the laser's resonator." The COIL "radiates only in a single line at 1.315 µm"

All these defence lasers are designed to deliver burst of several MW in a few seconds and not to provide CW power over long period. **They are not interesting candidates for Power Space Transportation.**

5.6.2 High power CO_2 Laser

This type of laser is mainly developed for industrial application (welding, cutting). The emission wavelength is 10.2 µm. High power laser (pulsed) were developed mainly for scientific application

The emitted radiation is given by the energy transfer between two vibrational levels of the CO_2 molecule. The energy transfer from lower level to upper level is performed thanks to an electrically excited N_2 molecule (Figure 5.6.2/1)

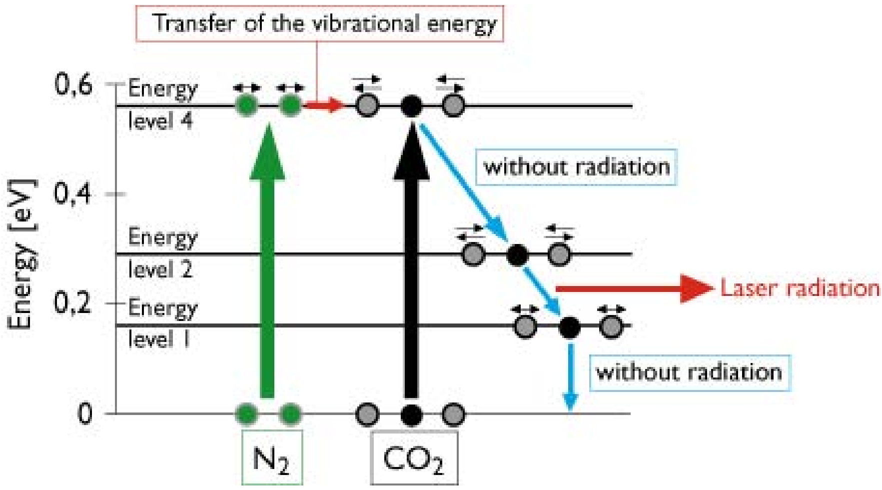


Figure 5.6.2/1: Energy transfer diagram for CO_2 radiation

The output power is proportional to the molecular flux (Gas flow). 10% Plug-in efficiency could be obtained with a correct dissipation of the thermal energy (gas flux, heat exchanger).

Long coherence CW length emission can be obtained (narrow frequency bandwidth)

The most powerful CW output for industrial laser is 50 KW. The volume of the laser is large enough (several cubic meters) (Figure 5.6.2/2).

CO_2 laser is an interesting candidate for Power Space Transportation

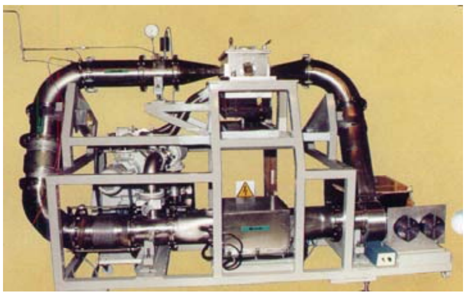


Figure 5.6.2/2: Prototype of High power CO_2 LASER (DRA courtesy)

Prototype of High power (1KW) CO_2LASER for Space LDAR application (DRA)

5.6.3 Free Electron laser

Free electron Laser (FEL) is unique laser that was recently developed. The electron beam will be used to produce infrared light. The main components are the undulator and the optical resonator. (Figure 5.6.3/1)

- The magnetic field of the undulator leads to a wiggling motion of the electrons that coherently transfers energy from the electron beam to an electromagnetic wave of a definite wavelength. In an FEL resonator the electromagnetic field is stored in an optical cavity that consists of two focusing mirrors facing each other. The gain of electromagnetic power per pass through the undulator (single-pass gain) and the corresponding losses at the mirrors or at elements of the beam line determine the electromagnetic energy stored in the resonator. A small fraction of that energy is coupled out by means of a hole or a transparent mirror.

- The optical resonator can be a confocal resonator or Fabry-Perot

The output power is in the range of several KW. Theoretically this type of laser can deliver radiation UV to far infrared. Presently most of the system are emitting in 3-6 µm wavelength range. One of the major drawbacks is the electron generation that require a large Cyclotron and this large electrical plant. The efficiency of the complete chain is very poor.

This type of laser is no longer considered for Space Power Transportation

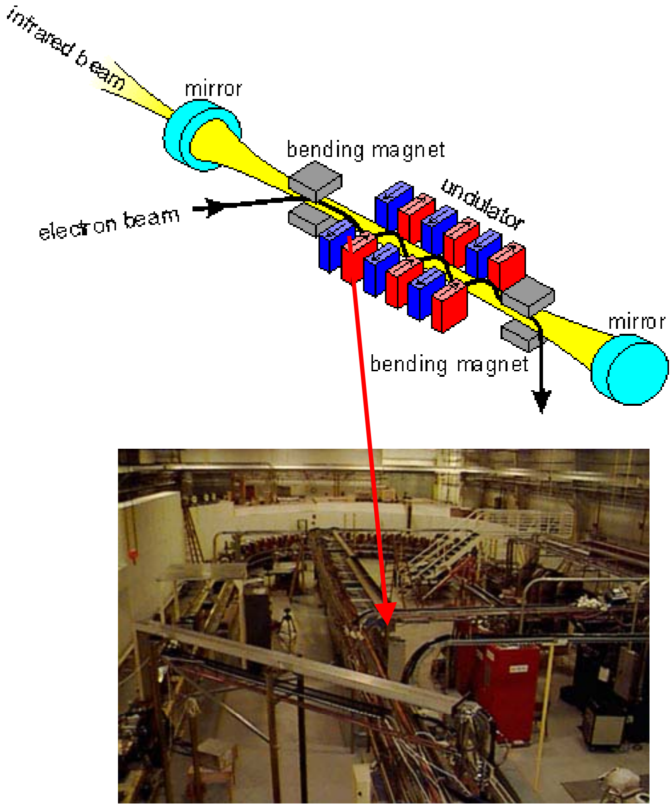


Figure 5.6.3/1: Free Electron Laser (from [6])

[6] Laser Acceleration Experiments at ORION-Robert L. Byer-2nd ORION Workshop February 18-20, 2003

6 THERMAL ENERGY CONVERSION

6.1 INTRODUCTION

The aim of this chapter is to assess the thermal to electrical conversion technologies suitable in the frame of Solar Power Satellites. The conversion subsystem is implemented on the consumer, i.e. the receiving system. The power is beamed from the power generation system with a dispersion, which has to be defined.

The overall view of the system is given on the figure 2/1.

With regard to the present definition of the system, the present chapter presents the way to use the thermal to electrical energy conversion technologies and compare the different ways.

The present work largely relies on previous studies achieved under ESA's contract and related to the space nuclear power systems.

6.2 STATEMENT OF THE PROBLEMATIC

6.2.1 General Problematic of thermal energy conversion is space

The light to electrical power conversion system consist of the following main functions:

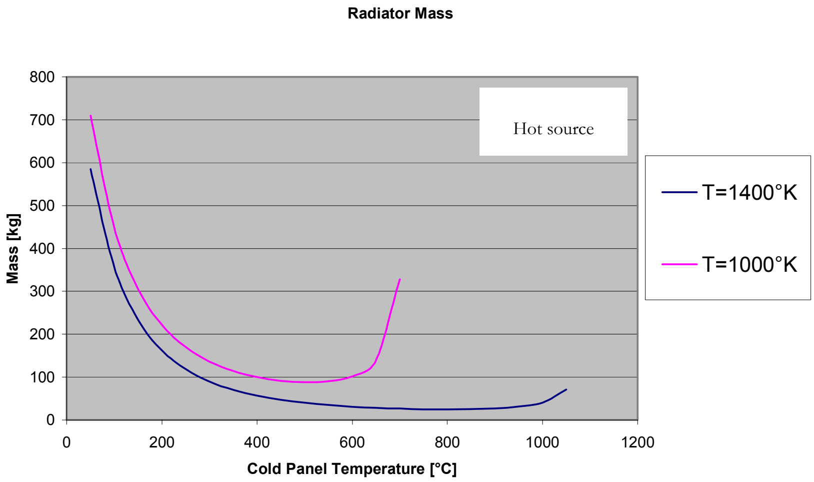
1. thermal power generation and transportation
2. thermal to electrical power conversion, including the converter itself and the cold source,
3. power conditioning

The power conditioning is considered in the frame of this study as a conventional technology, even if many issues are of importance in the overall efficiency assessment. Then in a first approach we will focus on the specific functions 1 and 2.

Generally speaking, the efficiency of the conversion is bound to the operating temperatures (Carnot's efficiency: 1-Tc/Th, where Tc is the cold temperature and Th is the hot temperature). That means that the higher the hot side operating temperature, the greater the efficiency.

Moreover, for a space system, as the cold temperature is obtained by radiating areas (no other way in the vacuum), the cold temperature may be as high as possible. Indeed the radiating area follows the Stefan-Boltzmann law: $Q_{rad} = \varepsilon\sigma T^4$ W/m^2. Then the higher is the temperature, the smaller is the radiator.

Last but not least, the association of the here above antagonist constraints leads to an optimisation of the system, in term of mass. The general curve of the radiator mass can be typically illustrated by the following curve, which takes in consideration the radiator efficiency and the conversion efficiency, and which can be applied for all conversion technologies:



Indeed:

- for the lowest temperature of the radiator, the efficiency is high. But unfortunately, the necessary area is to large and the mass budget is not optimised;
- for the highest temperature of the radiator, its area is small. But unfortunately, the efficiency is low, so a great amount of thermal energy has to be rejected. Then the mass budget is not optimised.
- Then an optimum wrt the system has to be found.

6.2.2 Problematic of Space power systems

With regard to the overall SPS, what are really the optimisation driving parameters?

In fact, for the receiver conversion subsystems, the here above rules can be applied. But when we consider the overall system, a parametric analysis is then necessary: we have to take into consideration the power generator subsystem, the beam generator, and the beam collector. Indeed, the specificity of SPS is to include several energy conversion subsystems:

- the solar power generator,
- the beam generator,
- the beam receiver,
- the thermal to electrical conversion of the receiver.

Then with regard to the features of all these subsystems and perhaps mainly the low efficiency of the beam generator, it is not possible to say without an in-depth analysis if the best way is:

1. optimisation of the mass of the conversion of the receiver,
2. or optimisation of the efficiency of the receiver.
3. Or finally and likely a medium way: to optimise the subsystem taking in consideration the system optimisation.

In case one, we save mass at the level of the conversion subsystem of the target. Well, but we need to receive more energy and generate more energy at the level of the SPS generators: what are the consequences on:

- the mass budget of the target, when we consider the mass of the beam collector,
- the overall mass budget, including the centralised power generator and the beam generator,
- the feasibility of the SPS, in term of sizing.

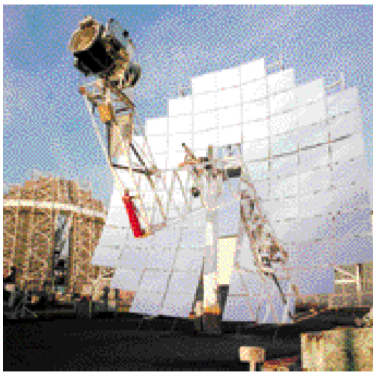
In other words, if we improve the efficiency of the conversion by a factor X, with a mass penalty of Y kg (for example) at the level of the radiator, what are really the consequences:

- at the level of the target in term of operability; we have to consider the different applications:
    - stationary satellites,
    - rovers,
    - transportation vehicles

  Likely the consequences of a mass penalty will not be the same for these different applications.
- at the level of the SPS:
    - for the beam, of which the power is multiplied by X,
    - for the centralised solar power system, of which the power is multiplied by a factor 5X to 10X with regard to the efficiency of the beam generator (assuming a 10 to 20% efficiency for the beam generator).

6.2.3 Generation of thermal power

For this function, the objective is to convert light energy into heat energy. As mentioned in the introduction, the heat source must be at high temperature with regard to the efficiency and the mass of the system.



For that, it seems that the best option is to re-use the principles applied and currently developed in the frame of terrestrial energies. At this time, we do not see any other solution. The here beneath pictures (Boeing and Sandia Nat.Lab) illustrate these principles. The solar light is concentrated with a parabola. Different technologies exist on Earth, but for this application the best suited parabola is a dish, with regard to the circular shape of the beam. Moreover, this type of parabola is the most adapted to reach high temperature.

The affordable temperature with the concentration of the laser beam has to be assessed. The terrestrial technological experiments give a temperature for the heated fluids of 600°C up to 1200°C. This temperature level allows to reach high efficiencies. We can consider that the affordable temperature in the case of the target of SPS could be the same.

Nevertheless it is also a question of technology for the parabola in the frame of space applications, issue that can not be discussed here. The third picture (NASA) shows a space concentrator. It can be noticed here that Nasa envisage the use of a second concentrator to reach very high temperatures (2000K).

These solar systems are generally coupled with thermodynamic cycles: Brayton or Stirling machines. One can notice that these converters are the same than the converters envisaged for space applications. Indeed, Stirling machines are currently developed and tested by US for a new RTG application while Brayton and Stirling are candidates in the frame of JIMO nuclear power system.

Generators are generally implemented at the focal point.

For terrestrial applications the cold source can be achieved by a convective cooler using the atmosphere or a coolant fluid. This allows to achieve compact cold sources.

In space, for flying spacecraft, the cold source must be a radiator, then the volume will be higher, and the implementation of the generator at the focal point is likely not the only solution. For planetary rovers, in case of existing atmosphere (e.g. on Mars), a convective cold source can be applied and could be the most attractive solution. Indeed, a convective cold source allows to reach lower temperatures while being compact.

6.2.4 Conversion technologies

Some potential technologies have been identified for thermal to electrical energy conversion in space. These technologies will not be described in detail here. They are mainly:

- thermoelectricity,
- thermo-ionic,
- Stirling machine
- Brayton machine,
- Rankine machine
- MHD

6.2.4.1 thermoelectricity

The thermoelectricity is generally recognised as having a low efficiency. That may be counterbalanced by the last results of R&D at JPL. The efficiency can reach a level of 15% (1000K) up to 20% (1200K-technology limits). But these performances need a 300K cold source, then a large radiator.

Generally for space applications, in order to minimise the mass, the system is optimised at higher radiator temperatures. But in the present case, as mentioned is section 6.2.2, it could be envisaged to privilege the efficiency and have a larger radiator. The integration of the parabola and the radiator could be an interesting option.

The interest of the thermoelectricity is to be free of moving parts.

With regard to the announced efficiency, it is underlined that the converter integration is not achieved, i.e. the technological problems related to thermal and electrical coupling remain to solve.

6.2.4.2 Thermo-ionic

Thermo-ionic has more drawbacks than advantages. The efficiency is low – no more than 10% - while technological problems are important and lead to a limited lifetime. So we will not go ahead with this technology.

6.2.4.3 Stirling

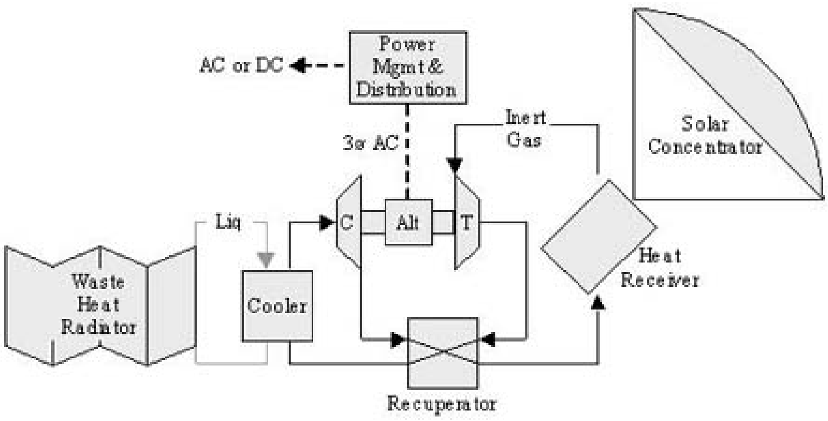
Stirling generators are not really free of moving parts, but they are an attractive solution in term of efficiency and mass. They have good performances are they are compact without rotating parts or risk of leakages. So they are good candidates (e.g. RTG, Jimo).

For example, the ASCS or SRPS (i.e. the RTG coupled with Stirling generator) reaches a 28% (23% for the overall system) efficiency between 950K (hot source) and 400K (cold source). That are really good performances at this low temperature level.

Higher efficiencies – 35 to 40% - are announced as affordable, mainly using higher temperatures.

6.2.4.4 Brayton cycles

Brayton cycle is also considered as an attractive solution, even if it relies on turbo-machinery. The affordable efficiency is between 25% and 35%. Many parameters drive this value. The temperature difference must be high to reach this efficiency: 1200K up to 1500K for the hot source, 300K for the cold source.



The Brayton cycle is interesting with very high temperature of the hot source. The technological issues (e.g. bearings) are not advantages but they are not considered redhibitory issues.

Brayton is attractive for high power ranges.

The here above figure has been published by NASA, in the frame of solar thermal power systems studies. The expected efficiencies are 30%.

6.2.4.5 Rankine cycle

Rankine is the best solution on Earth to convert thermal energy in electricity. The main drawback for space application is the 2 phase process. In fact without gravity, it is not simple to deal with the separation of 2 phases fluids.

The hardware relies on the same components that Brayton cycle, i.e. turbomachinery.

6.2.4.6 MHD converters

These converters have the interest of a good efficiency (at least as high than Stirling) while they are free of moving parts. The mass budget seems attractive. The technology is not mature at the time being. This process can cover from low power range (i.e. 100We) up to high power ranges (100kWe)

6.3 SPS TARGET SYSTEMS

Further to the here above analysis, the objective is to assess what could be the overall design of the SPS target system.

Nevertheless, for a comparative study, it is necessary to have precise inputs related to:

- the optimisation rules (efficiency or mass?),
- the power ranges,
- the affordable high temperature.

At this stage of the study, it is proposed to work on the following assumptions:

- power range: 1kWe and 100kWe will be considered
- affordable temperature: 1200 up to 1500K.

Some indicative data are given here under. They are to be considered as order of magnitude, as it is not possible to give precise data at this stage of the study. The here under data do not take in consideration the design and technical data related to the structures and heat transport. Their only use is restricted to orders of magnitude giving trends for upper level assessment.

➢ Attention is drawn particularly for thermoelectricity, for which it is necessary to spread the heat on a surface. Then the heat transportation subsystem is consequently penalizing in term of mass. This does not appear in the following tables.

➢ The parabolic dish has not been included in these balances. It could be considered that this subsystem is not the most critical in term of mass (high power density of the laser beam, lightweight structure).

6.3.1 Low power range (1kWe)

For that range, and with regard to the general considerations relating to the converters, the technologies to be selected are:

- thermoelectricity
- Stirling
- MHD

6.3.1.1 Thermoelectricity

Assumption: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	20%	
Input power	5 kW	
Rejected power	4 kW	
Radiator size	8 m2	#500W/m²
TE mass	4 kg	
Total mass	36 kg	Radiator specific mass: 4kg/m² Heat transportation mass not included

Assumption: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	8%	
Input power	13 kW	
Rejected power	12 kW	
Radiator size	1,2 m2	#10kW/m²
TE mass	4 kg	
Total mass	10 kg	Radiator specific mass: 4kg/m² Heat transportation mass not included

6.3.1.2 Stirling

Assumption: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	30%	Order of magnitude
Input power	3 kW	
Rejected power	2 kW	
Radiator size	4 m2	
Stirling mass	25 kg	ASCS: 0,04 kg/W
Total mass	41 kg	Radiator specific mass: 4kg/m^2

Assumption: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	20%	Order of magnitude
Input power	5 kW	
Rejected power	4 kW	
Radiator size	0,4 m2	
Stirling mass	25 kg	ASCS: 0,04 kg/W
Total mass	27 kg	Radiator specific mass: 4kg/m^2

6.3.1.3 MHD

Assumptions: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	40%	Order of magnitude
Input power	2,5 kW	
Rejected power	1,5 kW	
Radiator size	3 m2	
Converter mass	25 kg	Odm :600 kg for 100kWe
Total mass	37 kg	Radiator specific mass: 4kg/m^2

Assumptions: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	20%	Order of magnitude
Input power	5 kW	
Rejected power	4 kW	
Radiator size	0,4 m2	
Converter mass	25 kg	Odm :600 kg for 100kWe
Total mass	27 kg	Radiator specific mass: 4kg/m^2

6.3.2 High power ranges (100kWe)

For this power range, the proposed technologies are:

- thermoelectricity
- Stirling
- Brayton
- MHD
- Rankine

6.3.2.1 thermoelectricity

Assumption: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	20%	
Input power	500 kW	
Rejected power	400 kW	
Radiator size	800 m2	Radiator not feasible ?
TE mass	400 kg	
Total mass	3600 kg	Radiator specific mass: $4kg/m^2$

Assumption: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	10%	
Input power	1000 kW	
Rejected power	900 kW	
Radiator size	90 m2	
TE mass	400 kg	
Total mass	760 kg	Radiator specific mass: $4kg/m^2$

6.3.2.2 Stirling

No data available

6.3.2.3 Brayton

Assumptions: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	27%	Order of magnitude
Input power	370 kW	
Rejected power	270 kW	
Radiator size	540 m2	Feasible ?
Converter mass	400 kg	Order of magnitude, 2 machines 50kWe
Total mass	2640 kg	Radiator specific mass: $4kg/m^2$

Assumptions: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	15%	Order of magnitude
Input power	650 kW	
Rejected power	550 kW	
Radiator size	55 m2	
Converter mass	700 kg	Order of magnitude, 2 machines 50k
Total mass	920 kg	Radiator specific mass: $4kg/m^2$

6.3.2.4 MHD

Assumptions: the efficiency is privileged.

		Comments
Hot source	1200K	
Cold source	300K	
Affordable efficiency	40%	Order of magnitude
Input power	250 kW	
Rejected power	150 kW	
Radiator size	300 m2	
Converter mass	700 kg	odm
Total mass	1900 kg	Radiator specific mass: 4kg/m^2

Assumptions: the mass is privileged.

		Comments
Hot source	1200K	
Cold source	700K	
Affordable efficiency	20%	Order of magnitude
Input power	500 kW	
Rejected power	400 kW	
Radiator size	40 m2	
Converter mass	700 kg	odm
Total mass	860 kg	Radiator specific mass: 4kg/m^2

6.3.2.5 Rankine

No data available

6.4 CONCLUSIONS

It is not possible to conclude here because:

- the optimisation has to be achieved at the system level.
- The here above data are only order of magnitude (e.g. wrt the radiator specific mass, other assumptions may be used, which could change the conclusions).

For low power range (1kWe):

- in case of mass optimisation, TE appears as the lighter technology. Unfortunately, this mass saving is expensive in term of input power. A remark with regard to the US strategy in the frame of dynamic RTGs: the objective of the dynamic cycle is not to improve the specific mass of the conversion system. The objective is to save Plutonium. We remind that the mass of "conventional" RTGs (i.e. using thermoelectricity) consists of more than 80% of Pu. The Stirling machine is heavier, but divides the Pu mass by 3.
- In case of efficiency optimisation minimising the input power, Stirling and MHD converters are equivalent, but Stirling is under tests, MHD (free of moving parts) is under studies.

For high power ranges (100kWe):

- Thermoelectric converters lead to:
    - a problem of radiator size in the case of efficiency optimisation,
    - a problem of efficiency, i.e. input power, in case of mass optimisation.
- Brayton and MHD are consequently recommended. MHD seems the most attractive, but, once again, Brayton is under tests, MHD (free of moving parts) is under studies.

Finally, the systems efficiencies could be improved by increasing the hot source temperature, which is likely affordable. This is valid for all technologies excepted thermoelectrics.

7 RF POWER 2

7.1 INTRODUCTION

This chapter reviews up to date technical and scientific knowledge on microwave and WPT technologies in order to subsequently analyse the technical feasibility of using microwaves to remotely provide power to Space exploration systems.

In the first section, the geometry and main elements constituting a microwave WPT system are presented; the most helpful formulas for the dimensioning of these different parts are established, using hypothesis applicable to the foreseen applications foreseen. It is then shown that using microwaves for transporting energy on the very long distances foreseen in the different applications may in some cases be impractical. Microwaves may however be a possible candidate for some other applications, particularly when solutions using lasers may not be practical due to the presence of strong attenuation at laser frequencies.

In the second section, an analysis of the most appropriate microwave frequencies for WPT in Space is provided, based on regulation and electromagnetic compatibility constraints and technology availability and performance.

The third section provides an overview of up to date microwave technologies that may be used in the design of WPT systems. It mainly addresses the technology of microwave power generation and microwave to DC power conversion.

The fourth section is dedicated to an overview of possible technical solutions to address the problem of beam pointing and focusing.

Finally, among the various applications addressed in this study, only two can make use of microwave WPT in a practical fashion. All along these lines, more details and directions are given for these applications and technological researches that may further be necessary for their development are identified.

7.2 GENERALITIES ON WPT SYSTEMS AND MAIN FORMULAS

This section starts by a short description and reminding of what is a microwave WPT system and pursues by establishing useful formulas that can be used in the dimensioning of the main parts of the system and in deciding about the feasibility of using microwaves for given WPT applications.

7.2.1 WPT SYSTEMS

A microwave WPT system is generally consisting of two main units: the projecting unit (PU) and the collecting unit (CU).

The projecting unit is generally situated close to the main power source (electricity grid, photovoltaic cells and PMAD). Its role consists in converting the DC electricity power into microwaves. The generated microwaves are then focused into a beam by several means but all of them using an antenna to radiate the microwave energy out of the PU towards the target which consists in the collecting unit. The PU is usually designed to provide a microwave beam which is directed towards the center of the collecting area and a beam focus angle such that most of the energy radiated by the beam is intercepted by the collecting area.

The CU is usually situated close to the systems that will use the energy. This may be on top of an exploration robot or at the vicinity of a human base on the Moon. The role of the collecting unit is to intercept the microwave power contained in the beam projected by the projecting unit and convert this power into a DC electricity form that can be conveniently used for powering the target utilization. The most conventional design of a WPT collecting unit uses an area of rectennas to collect and convert the incident microwave energy.

The main parameters having influence on the dimensioning of the different parts of a WPT system are:

- Wavelength (or frequency) of the microwaves
- Efficiency of the collecting unit
- Efficiency of the projecting unit
- Total power required at system output
- Distance between the projecting and collecting units
- Physical microwave propagation constraints

Propagation constraints can be resumed by saying that the longer the distance between the PU and CU, the thinner the beam must be kept and thus the larger the projecting antenna diameter must be made.

Other constraints impose limits on dimensions that can be established for a given system. For instance, rectennas are usually designed to operate optimally at a given power density. Higher power densities may lower the performance and even destroy the rectennas. This provides a limit to the projecting antenna gain which must not be so high as to produce beam power densities in excess at the collecting location.

7.2.2 Dimensioning formula

To illustrate the principles addressed in the preceding paragraph and provide a more useful approach to the designer of WPT systems, let us try to treat a general problem of microwave WPT, whose main geometrical assets are depicted in Figure 7/1.

The projecting antenna is assumed to be a circular aperture of diameter D_p. If the polarization and phase are supposed to be uniform in the aperture, the electric field illumination at a given point P of coordinates ρ and ϕ, can be characterized by a scalar function $f(\rho,\phi)$. It can be demonstrated that the far field generated by this aperture is proportional to the Fourier transform of the illumination function over the

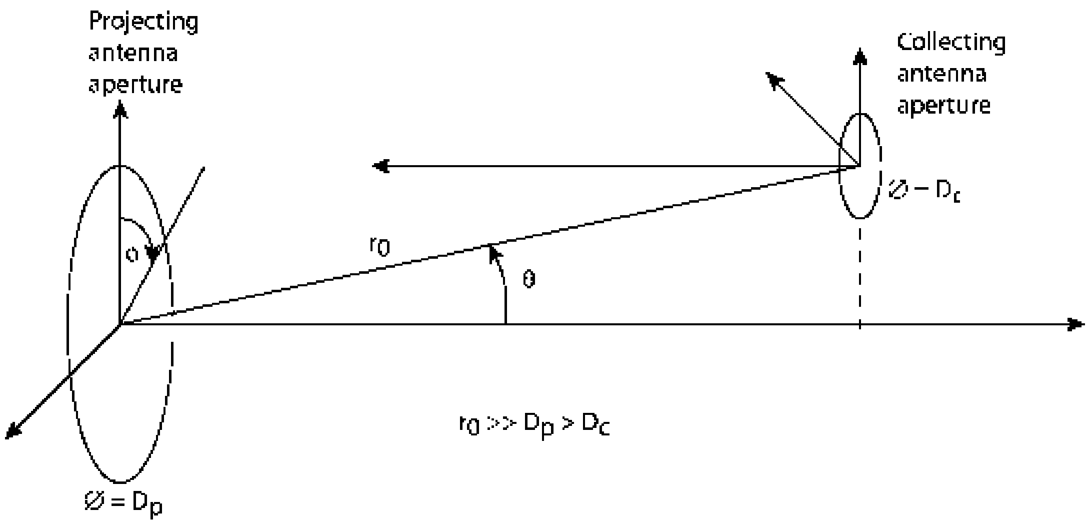


Figure 7/1: Geometry of a microwave WPT system

aperture, which can be demonstrated to be reduced to a function of θ in case of circularly symmetric illuminations:

$$F(\theta) = j\frac{2\pi}{\lambda^2}\int_0^{D_p/2} f(\rho)J_0(\frac{2\pi\rho}{\lambda}\sin\theta)\rho d\rho$$

where λ is the microwave wavelength used and J_0 the zero order Bessel function.

Now let us assume a 10 dB taper Gaussian illumination of the aperture, described by :

$$f(\rho) = e^{-1.1513\cdot(\frac{2\rho}{D_p})^2}$$

The so illuminated aperture radiates in free space and produces a beam that propagated towards infinity while exhibiting different properties at different regions of space (Figure 7/2) From the aperture to a distance of approximately D^2/λ, the energy flux is almost dispersionless. The field is concentrated into a cylinder of the same diameter that the aperture. This region is called the Rayleigh region. From D^2/λ to $2D^2/\lambda$, lies the Fresnel region which corresponds to a transition zone where the field distribution evolves gradually from the illumination function at the aperture to the one of the far field radiating diagram. The far field region, also called Fraunhoffer region starts at distances above $2D^2/\lambda$. In this region, the wave front can be assumed spherical and the field energy produced at a given point decreases as the square of its distance from the aperture.

The far field produced by the cylindrical symmetrical illuminated aperture is then characterized by the function:

$$H(\theta) = \frac{F(\theta)}{F(0)}$$

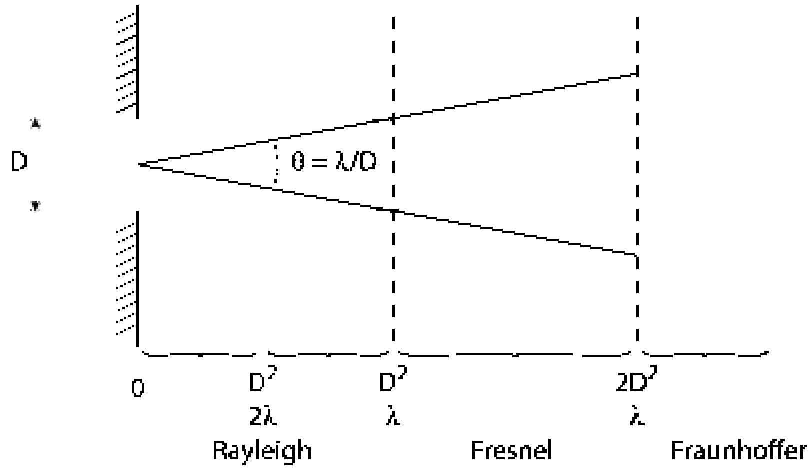


Figure 7/2: Simplified representation of the different regions of the field diffracted by an illuminated aperture.

This function is represented on Figure 7/3. The angle at -3dB of the main lobe and the relative amplitude of the first side lobe can be evaluated from this curve with respective values of 0.792λ/D radians and -24.36dB.

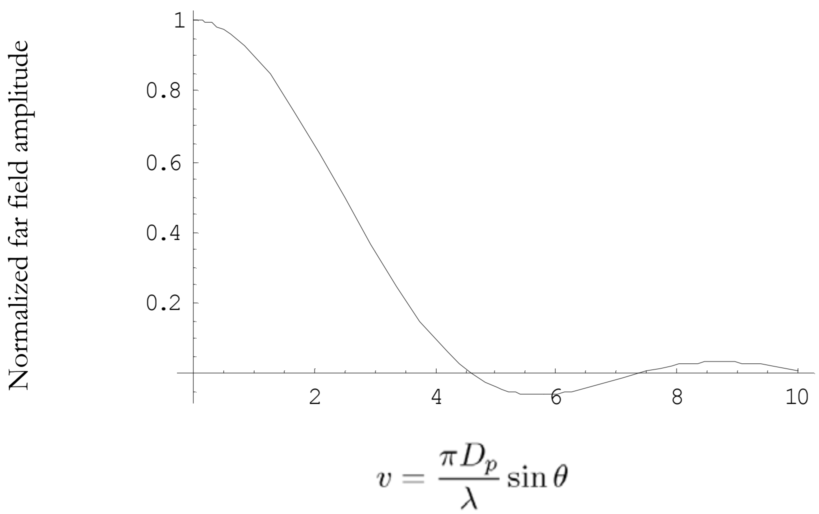


Figure 7/3: Normalized far field radiation function for a 10dB taper Gaussian illuminated aperture

In the microwave WPT applications foreseen in this study, the distances are very large compared to the antenna dimension. It is then a good approximation to consider that the field produced at each point of the collecting aperture is essentially the same. It is equivalent to say that we assume the gain of the collecting antenna to be equivalent to the one of a uniformly illuminated circular aperture.

The far field created by the illuminated projecting aperture at a given point M corresponding to the center of the collecting area and of spherical coordinates r, θ and ϕ in the projecting antenna coordinates, is given by:

$$\mathbf{E}(r,\theta,\phi) = \mathbf{A}E_0F(\theta)$$

with

$$\mathbf{A} = \frac{\lambda e^{-jkr}}{2r}(1+\cos\theta)(\hat{\theta}\cos\phi - \hat{\phi}\sin\phi)$$

It is then easy to demonstrate, with the hypothesis presented above, that the ratio of the power at the input of the projecting antenna to the power delivered at the output of the rectennas situated at a distance r from the projecting antenna and at an angle θ from the projecting aperture axis can be written as:

$$\frac{P_{out}}{P_{in}} = \eta_p\eta_c \cdot 0.6396 \cdot \left(\frac{D_c}{D_p}\right)^2 \cdot \frac{\lambda^2}{r^2} \cdot (1+\cos\theta)^2 \cdot F(\theta)^2$$

In the most favorable condition, where the projecting antenna axis coincides with the collecting antenna center, this formula can be simplified to give:

$$\frac{P_{out}}{P_{in}} = 0.556 \cdot \eta_p\eta_c\eta_{prop} \cdot \left(\frac{D_pD_c}{\lambda r}\right)^2$$

The parameters η_p and η_c occurring in this equation are the power efficiencies at the PU level and CU level respectively. η_p is generally consisting of two terms, the generator to antenna mismatch efficiency and the radiation efficiency of the antenna, whereas η_c is constituted of the antenna to rectifying circuit mismatch efficiency and of the RF/DC power conversion efficiency. P_{in} may also be regarded as the primary power supplied to the projecting unit, provided a DC/RF power conversion efficiency term is added to the η_p definition to account for the power loss in the RF generator.

To illustrate the use of this formula, let us examine the application case of a SPS in sun synchronous LEO beaming power to a satellite platform in EO collecting power with a 3 meters diameter antenna. Distance is approximately 45000km. Let us use choose a frequency of 35GHz as an example. First, we need to be sure that we fall in the range of parameters where the approximations used for the derivation of the above formula are valid. We need to be certain that we are in the far field region, for which the Fresnel diffraction approximation that we used in the derivation of the far field is correct. At 35 GHz, if the collecting antenna situated at 45 000 km must be in the far field region, a projecting antenna of no more than 600 meters diameter must be used. Of course we will limit our analyses to diameters well below this limit. The system falls clearly in the hypothesis of antenna diameter very small compared to the transmitting distance and the formula above is valid. The Figure 7/4 ives the power efficiency of this WPT system case as a function of the projecting antenna diameter. We can notice that with such large distances, the efficiency that can be obtained from a microwave wireless power transmission is not surprisingly very low. The present study will try to analyze if ameliorations to these efficiency levels can be brought from technological solutions and although identify the most appropriate range of distances and applications for which microwave WPT technology is practical.

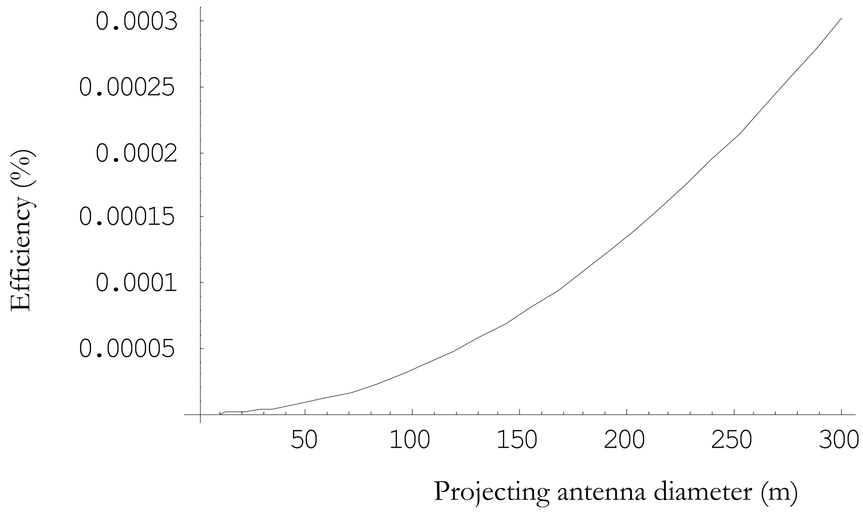


Figure 7/4: Power efficiency estimation for a WPT application case with distance equal the 45000 km, frequency equal 35GHz and receiving antenna diameter of 3m.

For the sake of comparison, Figure 7/5 valuates the power transmission efficiency for the same distance but now considering a 20 m diameter collecting antenna. As an example, to get 10kW out of the collecting system with a 2500 m diameter projecting antenna, 1 MW of power has to be available at the input.

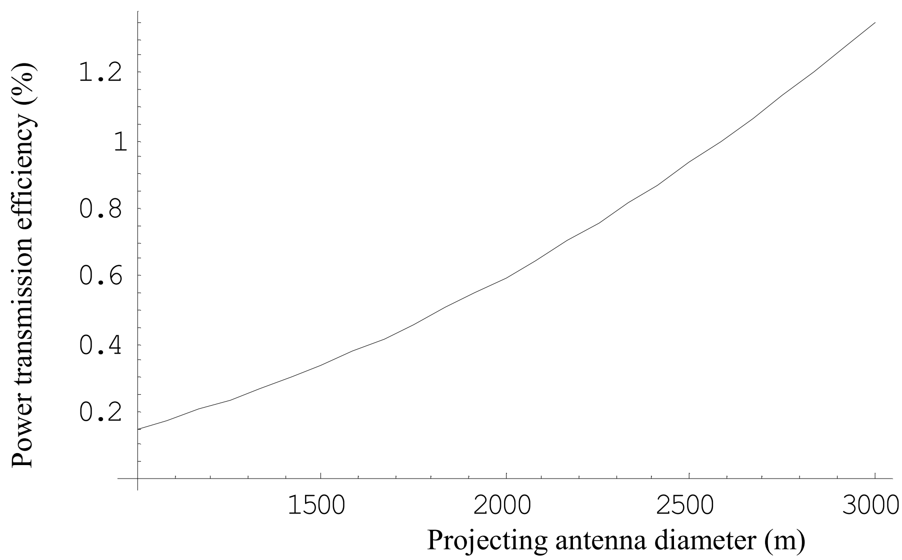


Figure 7/5: Power transmission efficiency calculation as a function of projecting antenna diameter for an application case where the distance is 45000 km, the collecting antenna diameter is 20 meters and the microwave frequency used is 35GHz.

These calculations are clearly illustrating the fact that wireless power transmission by microwave should be reserved to cases where the transmission distance is not too long, or where collecting and projecting antenna can be made large. In the case of the foreseen applications, the collecting antenna is generally not very large, because it is mounted on an OTV or on a rover, or also because building large structures on the Mars surface is not presently to our reach. Consequently, most of the foreseen applications will fall into a range of low efficiency power transmission. Nevertheless, when solutions may exist to alleviate the problem, they will be discussed in the following sections of this document.

One of the most obvious solutions to increase the power transmission efficiency consists in the use of higher frequencies. Antenna gain is usually limited to $G<\pi^2D^2/\lambda^2$. Shortening the wavelength allows one to greatly increase the antenna gain for a fixed antenna size. However, as we will see in the following section of this document, there is a variety of tradeoffs in choosing the optimum operating frequency of a microwave WPT system. Generally, increasing the frequency also leads to a decrease in the efficiencies of the various parts of the system. It is thus conceivable to think that an optimum frequency exists between 2.45GHz for which we know that high efficiency of RF power generators and rectenna is demonstrated but for which very large antennas are required and on the other hand, frequencies over 100 GHz, for which antenna sizes are more realistic but for which it is very difficult to obtain high efficiencies of the power conversion devices.

Let us mention one last point. In the above calculations, a Gaussian taper illumination was assumed for the sake of simply deriving a realistic relationship for the power transmission efficiency. Other kind of illumination taper would yield to different expressions of this efficiency. In some cases, it is even favourable to depart from the use of a Gaussian taper, as was mentioned by Zepeda et al.[7], in a recent paper. In this work, they have analyzed the influence of projecting antenna illumination taper on the efficiency of the WPT link. One of the goals for this work, was to find a taper that would allow a more uniform distribution of the thermal constraints on the surface of a projecting phased array antenna in Space, instead of having a concentration of thermal constraints at the center of the phased-array, as produced when a Gaussian taper is used.

Finally, although one might consider using high power laser beaming instead of microwave when small antenna aperture sizes limit the efficiency of WPT systems using microwave, there are cases where the use of laser power transmission is precluded. One such case is the one of transmitting power to the Mars surface from an orbiting SPS in the presence of dust storms. Laser in the visible region would definitely be scattered by the particles and the beam would then suffer a very strong attenuation. For such a case, microwave may still be a very good approach provided that dimensioning is made correctly and that it leads to realistic projecting and collecting systems sizes.

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[7] Zepeda, P. , Chang, K., Little, K. ,"Optimal Antenna Taper Design for a Sandwich Transmitting Array In Space Solar Power Satellite", IAC-02-R.2.10, International Astronautical Congress, Houston, Texas, 2002.

7.3 CHOICE OF FREQUENCY FOR WPT BY MICROWAVES

As previously mentioned, there are various tradeoffs to consider when choosing the most appropriate frequency for a WPT system. We have already discussed the dimensioning aspect of the problem, but other aspects to consider are the availability, performance and cost of the technology, attenuation of beam during propagation (which has not been taken into account in the dimensioning formula given in the first section of this document), and thermal management issues. Safety with respect to living bodies and surrounding electronic equipments is also a very important issue. Regulation issues regarding the frequency spectrum allocation to other utilizations are also important. In this section we will briefly run through each of these topics and try to get a clue about the most appropriate value to use for the operating frequency of WPT systems in the applications foreseen in this study.

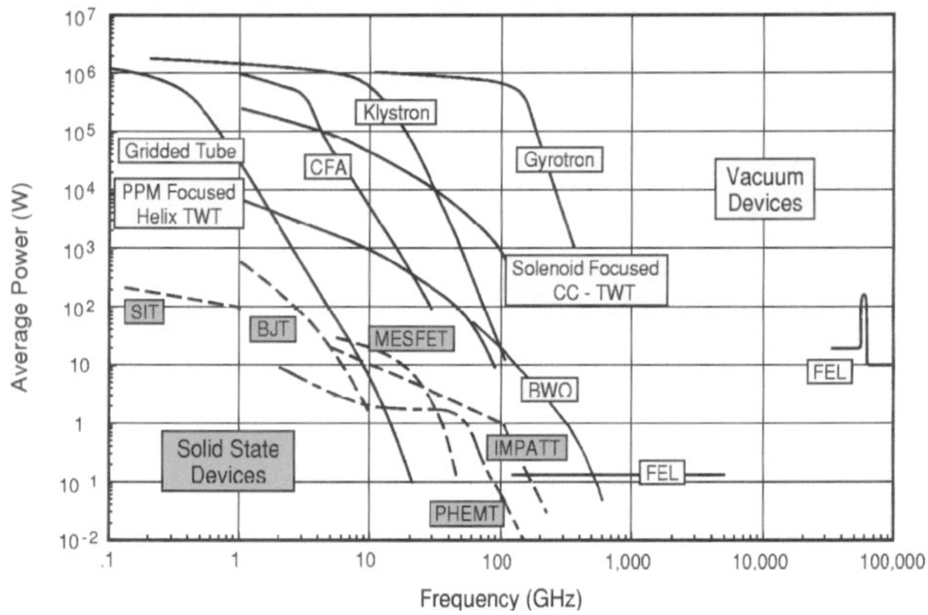

Figure 7/6 : Power and frequency applicability of microwave power generator technologies (Reproduced fromProceedings of the IEEE[8])

7.3.1 Technology availability, performance and cost

An entire section of this document is dedicated to an up to date technical overview of the most important parts of a WPT system. In this section we will then only address the aspects that are of primary concern in the choice of a frequency. Other more detailed technical solutions will be left for a presentation in this subsequent section.

[8] "Scanning the Technology – Vacuum Electronics at the Dawn of the Twenty-First Century", Granatstein, V.L., Parker, R.K., Proceedings of the IEEE, Volume 87, N°5, May, 1999

7.3.1.1 Microwave Generators

Figure 7/6 illustrates the current availability of generators as a function of frequency and output power. In the range of applications that we are interested in, because efficiencies will remain low, the projecting power will have to be high in order to get the necessary power at the utilization. This total projecting power can be provided by a single high power source or by an array of coherent lower power sources. We will below consider the available technologies from the one delivering the less power to the one delivering the highest power.

7.3.1.1.1 Solid State

Solid State Power Amplifiers are generally preferred to microwave tubes when power and frequency requirements can be met, because they can be powered using low voltage and because they can be conditioned in low volume easy to integrate packages. However, they usually exhibit lower efficiencies than microwave tubes. Recent advances in the design of SSPA have allowed the achievement of high Power Added Efficiency (PAE > 80% at C band) for harmonics controlled class E and F power amplifiers, PAE > 40% at Ka band and PAE < 20% at 60 GHz. It can be seen that efficiencies are generally much lower at higher frequencies and designs at these frequencies are also limited by the power density that transistors can sustain (4 W/mm of gate periphery for GaAs FETs). Highest power designs at Ka band for example necessitate the use of large water cooled radiators even for delivered output power of less than 10 W[9]. This is to be mitigated by the fact that a 2.6 W Ka-band amplifier was successfully demonstrated on the DeepSpace 1 mission[10]. It is expected that performance will increase in the 20 years to come under the pressure of direct to satellite communication markets but these improvements will not necessary allow SSPA to get better than microwave tubes in terms of power handling, frequency of operation and thermal management integration capabilities. One of the most promising directions for improvement is the development of new MMIC designs processed on GaN semiconductor materials[11]. GaN devices will allow the circuit to operate at higher frequencies, thus decreasing the size of heat dissipation radiators necessary to keep the junction temperature below the threshold for characteristics degradation. They will also work at higher voltages and consequently dissipate less power than GaAs devices at the same RF output power.

One of the main advantages of SSPA over microwave tubes is their possible integration with other active components on microstrip circuits. This usually leads to very easy to fabricate and light designs convenient

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[9] A 5-Watt, 37-GHz Monolithic Grid Amplifier , B. Dickman, D.S. Deakin, D. Rutledge, E. Sovero -IEEE Intl. Microwave Symposium, Boston, Massachusetts, June, 2000.

[10] M.K. Karnacewicz, W.J. Taft, S. Valenti, T. Renna, M. Hirokawa, S. Conway and L. Newman, 2.6 Watt K_a-Band Solid State Power Amplifier for Deep Space Communications. In: *Digest of Papers, Government Microcircuit Applications Conference* (1999), pp. 247–250.

[11] "High frequency GaN/AlGaN HEMT class-E power amplifier", Syed S. Islam and A. F. M. Anwar, Solid-State Electronics, Volume 46, Issue 10 , October 2002, Pages 1621-1625

for integration in Space systems at least for frequencies up to X band.

At higher frequencies, the required low operating temperature and the currently observed low efficiencies necessitates that large radiators be used to dissipate the heat losses generated at each SSPA, thus making SSPA much less convenient over microwave tubes for such applications.

As a resume, it can be concluded that the use of SSPA in microwave WPT projectors must be limited to designs at X band or below. It must noticeably be mentioned that many designs and SPS architectures have been proposed at 2.45GHz and 5.8GHz ISM bands. In these bands, many commercial applications are currently spreading very fast and consequently, costs of SSPA at these frequencies have dropped significantly. This may be a drawback when it comes to developing WPT systems in Earth environment because of possible interference with these systems. However, for applications in Space, there is no such constraint and designing a system at these frequencies would very much benefit from the economy of scale driven by exploding consumer markets for systems at these frequencies (WLAN, BlueTooth, …).

7.3.1.1.2 Microwave Tubes

Microwave tubes have been the components of choice for many applications because of their ability to provide high power output. Microwave tubes of different kind exploit different physical properties of electron dynamics[12]. However, using tubes in microwave WPT systems in Space may have several advantages. Tubes are powered using high voltages. This is challenging, but may represent an interest in Space because using high voltage busses could lower the heat dissipation and associated energy losses. Tubes can operate at high temperature. Stephan's law dictates that energy flux radiated by a black body is proportional to T^4. Radiators are consequently more efficient in dissipating the heat and also much lighter. Tubes are mostly insensible to radiations. They are high power densities devices, generally exhibiting high Power/Mass ratios. Finally, they most of the time exhibit higher efficiencies than solid state amplifiers.

We devote a complete section to a review on available tube technologies for the frequency spectrum of interest, further ahead in this document. Consequently, in the following lines, we will only analyze the status and performance of the most common devices.

For low frequency bands, magnetron is the component of choice. It is a high efficiency, rude and cheap device. At higher frequencies, anode heat dissipation is difficult to achieve and limits the availability of these devices, although interesting developments of miniature magnetrons are worth being noticed. Klystrons and TWT at these low frequency bands exist and are usually very high power systems with large dimensions, because the electron beam is linear and interaction distances at these wavelengths need to be large. At intermediate bands, klystrons are certainly the most interesting devices. They exhibit high output power capability together with high efficiency. In the millimeter range, for frequencies up to 100GHz, klystrons are still very attractive, particularly Extended Interaction Klystrons (EIK) which exhibit large

[12] "Review of high-power microwave source research", Steven H. Gold, Gregory S. Nusinovich, Rev. Sci. Instrum. 68 (11), November 1997, pp. 3945-3974

power output capability together with a low volume. Gyrotrons are relativistic beam interaction devices which require the use of high constant magnetic fields. Many designs have been produced that can deliver hundred of kilowatts of CW power at frequencies above 100 GHz. However, these designs are limited by the heating of the output window of the system which is generally the critical part of the system. It is not clear whether this window would still be needed in the Space vacuum. The high magnetic field is generally generated by superconducting magnets. Some designs exist that use coolant free superconducting magnets. However, these designs have never been tested in Space or in microgravity, and it is difficult to predict if they can successfully be used in Space.

To conclude on microwave generators, let us remember that the goal is to increase the frequency in order to reduce the antenna sizes. It is a fact that efficiency decreases when the frequency is increased. Output power also decreases, which means that more devices are needed to get the same overall radiated power, thus increasing the complexity of the system and associated cost. The increase in frequency also signifies that the same amount of power has to be radiated into a tighter surface. Eventually, it comes a point where heat dissipation may become critical. Increasing the frequency also signifies that we have to build phased array antennas in Space (output power from a single tube being insufficient). To safely point the beam in the direction of the target, phase control has to be performed on each radiating element of the array. This can be planned if the planarity of the phased-array aperture is guaranteed. Unfortunately, because of the long distances considered, large apertures are needed and consequently, it is not realistic to make such a hypothesis on the array planarity. Phase control has to be made through the use of adaptive algorithms or through the use of retro-directive phase conjugating networks. Each of these solutions very much rely on the ability to shift the phase of each radiating element in order to account for the deformation of the plane of the array or for the relative displacement of the target. At high frequencies, even a small deformation can lead to large phase rotations. Phase conjugating network or algorithms must have the ability to calculate and correct the phase very rapidly. It is then very challenging to design such systems and this of course brings the cost and complexity to a high level with current technology. The conclusion is that there must be a tradeoff frequency between the low frequency where antenna gains are too low leading to huge structures in Space and millimeter frequencies where low efficiency and high complexity of the system drive the cost to impractical skies. A more detailed study would be needed to identify this frequency but considering the abundance of high efficiency and mission qualified devices at Ka-band, a frequency in this region of the spectrum seems to be the most appropriate tradeoff. Let us make it clear that it is identified at a given point in time and that it is expected that this tradeoff frequency will shift upward to 60GHz and even higher in the future, while technology is improved and cost is decreased at these frequencies.

7.3.1.2 Rectennas and other RF/DC conversion systems

The most common way of rectifying microwave power to DC is to use a rectenna (rectifying antenna). It consists of an antenna which collects the incident beam energy and forwards it to a rectifying circuit, generally consisted by a Schottky diode. Correct filtering at the inputs prevents from radiating back any spurious that could be generated by the non linear diode and output filter is used to extract the DC signal from the rectifying circuit.

GaAs Schottky diodes are generally used in 2.45GHz and 5.9GHz designs, but nothing prevents them from being used in higher frequency designs also. Efficiencies of more than 90% have been reported on individual rectenna at 2.45GHz[13], whereas more than 70% has been obtained for a rectenna at 35GHz[14]. We do not know of any designs above 100GHz. Drift velocity of GaAs may become a limitation at some frequency above 40GHz and may necessitate the use of other semiconductors, but here again the physical principle would still be adequate and provide high efficiencies. Efficiency of individual rectenna is very much dependent on the series resistance of the diode. It is also very much dependant of the correct matching of the rectifying circuit to the antenna. The matching filter must match the impedance of the antenna to the one of the diode circuit at fundamental operating frequency while short circuiting harmonic frequencies to avoid that they radiate back to the antenna. This matching may be much more difficult to achieve at higher frequencies and would probably involve MMIC technologies for their practical realization.

However, we could conclude on the impact of rectenna technologies on the choice of the frequency, that it does not represent an issue. Rectennas at frequencies up to 60GHz could commonly be designed. Above 100GHz, design of such systems may prove to be very challenging, but there is no physical limitation of the principle beyond the technological difficulty of realizing the rectenna at these frequencies.

We present a more technical description of the design of a rectenna further ahead in this document and provide a deeper coverage of published data on performance of these devices. We also address the question of connecting an array of individual rectennas together in a not necessarily stable power density illumination condition.

Finally, it is worth mentioning a device which has been presented as a possible RF/DC conversion system[15]. It is called a Cyclotron Wave Converter (CWC)[16]. The principle consist is accelerating electrons in a focused beam. A RF interaction cavity where an axial magnetic field is present, is used to produce a rotation of the beam. Then the beam traverses a transition region where the magnetic field is tilted in the –z direction. This leads to a decrease of the tangential velocity and to an increase of the velocity in the z direction for the electrons. A collector is used to extract the kinetic energy of the electron beam as a DC

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[13] R.M. Dickinson, "Evaluation of a Microwave High-Power Reception-Conversion Array for Wireless Power Transmission" Tech-Memo 33-727, Jet Propulsion Lab. Cal. Inst. Technol., Mar. 15, 1975

[14] P. Koert and J.T. Cha, « 35 GHz Rectenna Development », in WPT-93 : First Annual Wireless Power Transmission Conference, Center for Space Power, Texes A&M University, College Station, Texas PP 457-466, 1993 and also T. Yoo and K. Chang, "Theoretical and Experimental Development of 10 and 35 GHz Rectennas", IEEE Trans. On Microwave Theory and Techniques, Vol. 40, N°6 June 1992, pp. 1259-1266

[15] V.A. Vanke, H. Matsumoto, N. Shinohara and A. Kita, "Cyclotron Wave Converter of Microwaves into DC", IEICE Transactions on Electronics, Vol. E81-C, N°7, July 1998, pp. 1136-1142

[16] United States Patent N°6,507,152

power into a resistance. Designs have been demonstrated at 2.45GHz and exhibit efficiencies > 70%.

However, these devices require a primary power source to be present to produce the initial high voltage for the electron acceleration. Nevertheless, such devices may become useful when large power densities not sustainable by conventional Schottky diode rectennas are used at the receiving site.

7.3.2 FREQUENCY ALLOCATION AND ELECTROMAGNETIC COMPATIBILITY

In this section, we analyze how current regulations on frequency allocation can influence our choice for a frequency that can be used in microwave WPT for the applications addressed in this study.

This problem is a crucial issue for SPS systems that propose to beam energy towards the Earth surface. Beaming power to other satellites or exploration systems in Space may necessitate similar care. However, we would like to concentrate mainly on applications that have the best potential of being realized. Among the foreseen applications, we will demonstrate that applications for provision of energy to systems on Mars are the one that are taking the best profit of microwave properties. Indeed, the presence of an atmosphere on Mars and the occurrence of dust storms are making it almost prohibitive to design a WPT system based exclusively on lasers. Indeed, optical depths at visible wavelengths range from as low as about 0.1 during seasons near Mars aphelion, to as much as 6 near perihelion during the years when planetwide or "global" dust storms occur. Optical depths in local and regional dust storms are likely to range up to even higher values. This is why using microwave in the design of remote energy provision system is a suitable solution and we will thus focus our discussions more specifically on the electromagnetic environment at the vicinity of Mars. Other applications around the Earth that this study is addressing, are also generally involving distances far too long for microwaves to be a practical solution.

Link	Frequency range
Space-to-Earth	2290 to 2300 MHz
	8400 to 8450 MHz
	31.8 to 32.3 GHz
Earth-to-space	2110 to 2120 MHz
	7145 to 7190 MHz
	34.2 to 34.7 GHz
Orbit-to-surface	435 to 450 MHz
	2025 to 2110 MHz
	7190 to 7235 MHz
	14.5 to 15.35 GHz
Surface-to-orbit	390 to 405 MHz
	2200 to 2300 MHz
	8400 to 8500 MHz
	16.6 to 17.1 GHz
Surface-to-surface	435 to 450 MHz
	390 to 405 MHz
	2025 to 2120 MHz
	2200 to 2300 MHz
Orbit-to-orbit	435 to 450 MHz
	390 to 405 MHz
	2025 to 2120 MHz
	2200 to 2300 MHz
	7190 to 7235 MHz
	8450 to 8500 MHz
Approach navigation and atmosphere radio science	8400 to 8450 MHz

Figure 7/7*:* Table of utilization of the frequency spectrum at the vicinity of Mars (Reproduced from D. Hansen et al.[17])

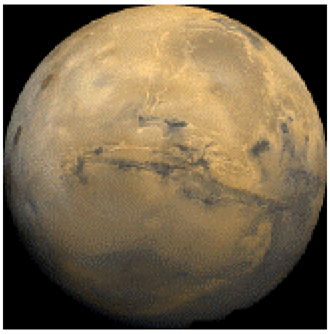
Figure 7/7 gives an overview of the frequency spectrum utilization in the Mars environment. Of interest to us, are frequencies above Ku-band, because of expected size reductions of projecting and receiving antennas at these frequencies. The quick overview on technology availability given above, have demonstrated that there is a tradeoff between the size reduction and the increase of the energy losses associated to the use of higher frequencies. We may then restrict our interest to a region of the spectrum situated between Ku-band and W-band. In Figure 7/7, only Earth-to-Space and Space-to-Earth communication links are concerned, more specifically at frequencies in the Ka-band (31.8 – 34.7 GHz). This leaves very much room for other microwave applications. This is also very interesting because it means that there is only few systems that may interact with WPT frequencies and that involving constructors of these systems in an electromagnetic interference protection and hardening process is easy

[17] D. Hansen, M. Sue, T. Peng and F. Manshadi, "Frequencies for Mars Local High-Rate Links", Nasa IPN-Progress Report, 42-153, 15 Mars 2003.

and would not necessary involve a high cost considering that Mars exploration is only at a beginning stage.

WPT applications are generally involving power densities much higher than telecommunication systems. Such communication systems are designed to have high sensitivity and good signal/noise ratio. Receivers of such systems are usually involving non linear devices and receiving a high power density signal, even at a frequency outside the band of such receivers, may still affect their characteristics and perturb their operation. This is why any communication system in the Mars vicinity or designed to work at the Mars surface, must be designed to filter out frequencies reserved for WPT use. The frequency allocation process is consequently something which must be discussed at the very early stage of Mars exploration, to account for the potentiality of using microwave WPT for energy provision to systems on the Mars surface.

One other issue that may be raised by microwave WPT systems is the high power density at the vicinity of the SPS projecting antenna. Let us indeed assume a 200 meters antenna diameter, projecting a 1 MW of microwave power at 35GHz. The Rayleigh region where energy is concentrated in a cylinder of same diameter than the projecting aperture extends to a distance D^2/λ. Calculation gives a distance equal to 4650 km. In this cylinder, the power density of the beam is equal to 100 W/m^2 or 10 mW/cm^2. This is an order of magnitude below that of the visible radiation energy received from the sun. This is just twice the European standard for safe illumination during 24h. Consequently, it is assumed that no harm is expected from such a system, provides that no flight crew is stationed in the beam. Electromagnetic interferences are of the same kind than the one already discussed above. WPT systems are usually using a CW microwave radiation and would not cause intermodulation products to fall into other systems receiver band, if the frequency is carefully chosen. However, filtering is still needed so as not to modify the receiver characteristics by non linear effects caused by a relatively large power signal, even outside the receiver's band.



Finally, attenuation of the signal on the beam path through the atmosphere of Mars is also an important issue. The Mars atmosphere is mainly made from Carbon Dioxide (CO2) - 95.32% ; Nitrogen (N2) - 2.7% Argon (Ar) - 1.6%; Oxygen (O2) - 0.13%; Carbon Monoxide (CO) - 0.08% and with some minor traces of water. Local dust storms usually happen quite often, while global dust storms are less frequent and sometimes do not happen for several years. Dust particles have diameters ranging from 0.1μm to 10μm. Many physical effects are involved in the beam propagation through the atmosphere. Diffraction by dust particles (negligible), absorption and scintillation in the ionosphere, molecular rotational absorption (CO, H_2O, O_3 or eventually CO_2), diffusion by aerosol and fog (haze), are effects that one must consider in such an analysis. D. Hansen et al. mention in their report, a Nasa study which has been made recently on the electromagnetic propagation properties of the Mars atmosphere, considering most of the effects listed above. The general conclusion is that the Mars atmosphere is generally much more transparent to microwave than the Earth atmosphere. They are giving figures of zenithal attenuation of 0.5 dB for both UHF and S-band, 1 dB for X-band, and 3.5 dB for Ka-band. Although attenuation at S-band is much lower, these frequencies are not practical for WPT applications because of the large size of the antenna that they require. Furthermore, a deeper analysis of these results and of the methodology used need to allow the use of these data as an input in the design of WPT systems. Indeed, we need to evaluate which effect is giving rise to the 3.5dB a Ka-band. We believe that it is certainly due to attenuation in the presence of dust storms and this value should be sensible to the dust mass loading and dust particle size distribution. Are these effects still strong at higher frequencies or do they correspond to a molecular resonance with no effect at other frequencies?

We may consider this problem open and will assume that there is a linear increase in the beam attenuation when the frequency increases. Once again, there is a tradeoff between the advantage of using smaller size antennas and the drawback of higher beam attenuation by the Mars atmosphere.

We lack more data to fully conclude, but we may consider that beam attenuation is not an issue. It is an input that the designer needs to account for when dimensioning the system, but it does not preclude the establishment of a technological solution as in the case of laser WPT systems.

7.3.3 Conclusion on the choice of a frequency

We have studied some of the most important aspects when trying to choose an operating frequency for a WPT system that could be designed to deliver electricity to remote systems in Space. Large distances involved in such applications represent the most crucial aspect and generally impose a large size for the antennas. Consequently, increasing the frequency could alleviate such a problem and lead to more practical designs. On the other hand, technology performance decreases at higher frequencies and so does the beam attenuation. There is a tradeoff between all these effects that must be found for a given design. This tradeoff may evolve with the advancement of the technology of microwave tubes and amplifiers in the millimeter region. We estimate that the large availability of mature and proven technologies in the Ka-band make solutions at these frequencies very convenient and practical. Cost of microwave tubes at these frequencies is kept low due to the existence of satellite communications applications. Rectennas at these frequencies have been built and demonstrated with efficiencies above 70%. Some work has still to be performed to adapt the technology to the requirement of Space and to the Mars environment (low operation temperature), however this is not a hurdle to the achievement of a technological solution.

It is expected that higher frequencies, probably in the 60GHz region, will be more suitable when performance and cost of devices in this region of the spectrum will be improved. There are many applications foreseen in this frequency band and it once again may drive the research and development and lead to components that could be favourably reused in future WPT systems in Space. We do not expect solid state technology to perform better at these frequencies and believe that TWT and Klystrons will remain much ahead in terms of power handling and efficiency. Solid state improvement must be sought for in the area of RF/DC rectification. Improvements in the design of GaAs diodes, design of rectenna in MMIC technology, use of other semiconductors like GaN, are some directions that can be followed for research in this area.

7.4 TECHNOLOGICAL OVERVIEW

This section provides an overview of up-to-date and available technologies of interest to the domain of microwave WPT.

We have demonstrated in the preceding section that only frequencies from the Ka-band and up can lead to acceptable elements sizes and power transmission efficiency. We also mentioned that efficiencies are decreasing with the frequency increase. Other technical considerations also limit the highest frequency that can be used. Indeed, such systems require a perfect control of phase distribution in the aperture of the antenna to safely and efficiently focus the beam on the target collecting antenna. This is very difficult to achieve at frequencies above 100 GHz. This is why we will focus this overview on technologies in the range of frequencies from 27GHz to 100GHz.

7.4.1 High power Microwave generators

7.4.1.1 Microwave solid state power amplifiers

Data that we have found on available or published work on microwave Solid State Power Amplifier at frequencies above 27GHz, show that Power Added Efficiencies (PAE) of the order of 40% at Ka-band and 20% at 60GHz. As an example, Figure 7/8 displays data for a GaAs MMIC amplifier developed at the Fraunhoffer institute (Germany) and delivering a 23dBm output power with a 22% PAE efficiency.

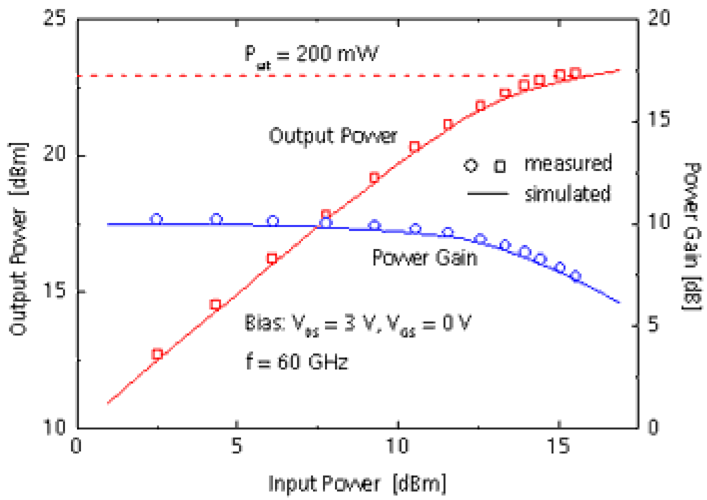


Figure 7/8: Measured power gain and output power of a 60GHz GaAs MMIC amplifier developed at the Fraunhoffer Institute and exhibiting 22% PAE.

Higher power output is currently obtained using power combining techniques giving rise to distributed amplifier implementations. Output powers of 5 to 10 W have been reported at Ka-band[18] and 2 W at V-band. However, power combining efficiencies are very high and PAE efficiencies at 35GHz drop below 20%.

Output power is limited to maximum junction temperatures and for MESFET GaAs devices; for example, this can be translated to a maximum power density of 4 mW/μm of gate length. Higher temperatures can be very interesting in Space to reduce the radiators mass. Larger bandgap materials could be successfully used in future amplifier design for this purpose. GaN is a promising material to this respect[19]. Other promising results have also been reported on InP/InGaAs heterojunction bipolar transistors at high frequencies[20].

Achieving the total power required by SPS-REPOSE application with microwave SSPA is challenging. Indeed, powers of the order of 1MW are required. At 35GHz, assuming a 5W Grid SSPA with 30% efficiency, this would necessitate the use of 600,000 devices. The estimated volume of one device, with its radiators is approximately 75 cm^3. The weight of such a device would be mainly consisting in the weight of the radiator, presumably aluminum, which would give a mass of 200g for each device. This gives a power/mass ratio of 25W/kg. This is to be compared with the 58W/kg achievable with a 1000 W Extended Interaction Klystron from CPI, or with the 125W/kg achieved by the VTA-6430A2 Travelling Wave Tube from CPI. This is more than a 5 fold ratio that power amplifiers have to improve in order to become competitive with high power tubes at these frequencies.

The conclusion of this overview is that SSPA cannot currently provide the power handling, power/mass ratio and efficiencies required for SPS applications in Space at the frequencies that would be convenient for these applications.

7.4.1.2 Microwave tubes

Microwave tubes also called vacuum tubes or electron dynamic devices, can be classified in different families depending on the kind of interaction that exist between the electron beam and the structure which it traverses or depending on the interaction with the electromagnetic wave. A very good review and classification can be read in the article of S.H. Gold et al.[21]

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[18] "A 5-WATT, 37-GHz MONOLITHIC GRID AMPLIFIER" Blythe Deckman, Donald S. Deakin, Jr., Emilio Sovero and David Rutledge, International Microwave Symposium, Boston, Massachusetts, June, 2000

[19] "High frequency GaN/AlGaN HEMT class-E power amplifier", Syed S. Islam, A.F.M. Anwar, Solid-State Electronics 46 (2002) 1621–1625

[20] "50 TO 70 GHz InP/InGaAs HBT AMPLIFIER WITH 20 dB GAIN" Thomas Morf, Dieter Huber, Alex Huber, Volker Schwarz, and Heinz Jäckel, Proc. 11th Int. Conf. Indium Phosphide and Related Materials (IPRM'99), vol. WeB 1-7, pp. 131–134, 1999.

[21] "Review of high-power microwave source research", Steven H. Gold and Gregory S. Nusinovich, Rev. Sci. Instrum. 68 (11), November 1997

MG5321 (E2V Technologies Inc.)

Frequency	35 GHz
V0	8.0 kV
I0	7.0 A
Power	10 kW (!!)
Efficiency	18%
Power/mass ratio	0.12W/g

Figure 7/9: Miniature magnetron developed by E2V Technologies, and available data

We will consider only 3 main kinds of microwave tubes, because of their degree of maturity and performance and because of their good coverage of the basic requirements in terms of frequency, power output and operating temperature. These are Klystrons (multi-beam or Extended Interaction Klystrons), TWT (linear TWT, helix-TWT) and Gyroklystrons, Gyro-TWT or gyrotrons, because of their ability to provide very high power at millimeter frequencies. Magnetrons will not be addressed because of their inherent limitation of working at high frequencies and would just like to mention very interesting designs that have been presented on miniature magnetrons operating at 35GHz (Figure 7/9).[22,23]

Klystrons are microwave devices that exploit coherent transition radiation from electrons. A typical klystron amplifier topology is shown on . An initially uniform electron flow is formed at the cathode and modulated by the input microwave field injected at the first cavity traversed by the electron beam. This modulation is such that electrons are forming bunches during their travel through the drift space separating the two cavities. Coherent radiation is generated at the second cavity when electrons are decelerated by the self produced field at the cavity gap.

[22] http://e2vtechnologies.com/

[23] A.N. Kargin, "Miniature synchronized magnetrons cm-range with output power 30-40 W, efficiency 50% for portable transmitters and satellite communication transmitters", ISTOK, Moscow, presented at UHF-99, International University Conference on Electronics and Radiophysics of Ultra High Frequencies, St Petersburg, May 1999.

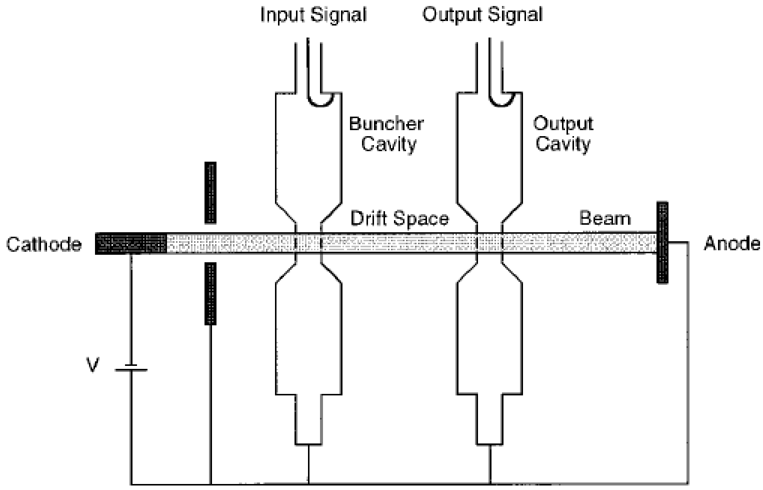

Figure 7/10: Schematic representation of the internal structure of a two-cavity klystron amplifier (reproduced from Gold et al.).

This linear configuration allows very high power and very efficient microwave power to be produced at frequencies in the C-band. Figure 7/11-a shows a drawing of a linear klystron at C-band (Courtesy of Thales Electron Tubes, France). Conventionally, a linear interaction configuration, however, does not allow for an efficient amplification at high frequencies, because of the limit in the breakdown electric field in the cavity gap.

Efficient deceleration of electron bunches in the cavity gap also requires the electromagnetic field to be localized in the resonator. This implies that the holes in the microwave structure, through which electron propagates, must have transverse dimensions lower than the produced resonator wavelength. At millimeter frequencies, this is impossible to realize practically and modifications to the conventional structure have been proposed (sheet-beam klystrons and multi-beam klystrons). Figure 7/11-b shows the detail of a resonator traversed by multiple holes through which the multiple beams produced by a multicathode electron gun can propagate.

Scaling a conventional klystron to higher frequency is limited by both the available cathode current density and magnetic focusing field. This usually implies a decrease in beam conductance. Since the efficiency is proportional to the beam conductance times the circuit impedance, the beam conductance decrease typically corresponds to a reduced output RF power. The extended interaction structure plays a crucial role to increase the circuit impedance. In EIK, the beam interacts with a ladder or periodic structure that increases the circuit impedance. The higher impedance of the EIK can compensate for the lower beam conductance, keeping the efficiency high in the millimeter scale circuits. At the same time, it also has the effect of enabling the use of lower Q output load leading to an increased bandwidth.

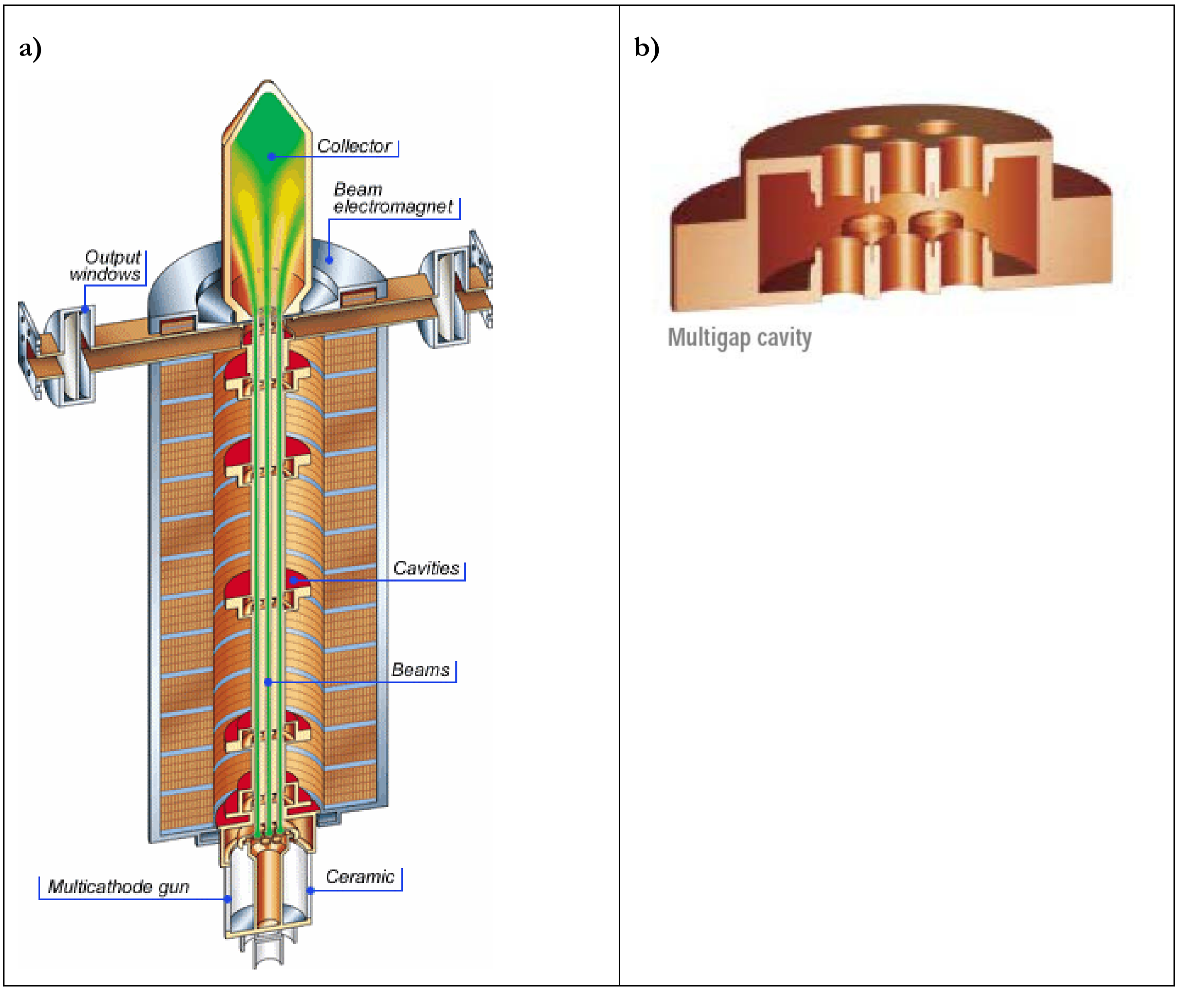

Figure 7/11: a) cut drawing of a linear multi-beam interaction klystron, showing the multiple resonating cavities where electrons bunches are decelerated to produce an RF field; b) Multigap cavity showing the holes in the microwave structure where the multiple electron beams can propagate (reproduced from Thales Electron Tubes).

Figure 7/12 shows data on available CW power output of some EIKs. It can be noticed that power of several hundred watts can be achieved at Ka-band. Figure 7/13 shows a 35GHz EIK developed at CPI, able of delivering 1kW of CW microwave power and having a mass of only 17 kg. This model is however is a water cooled EIK which could not be used in Space.

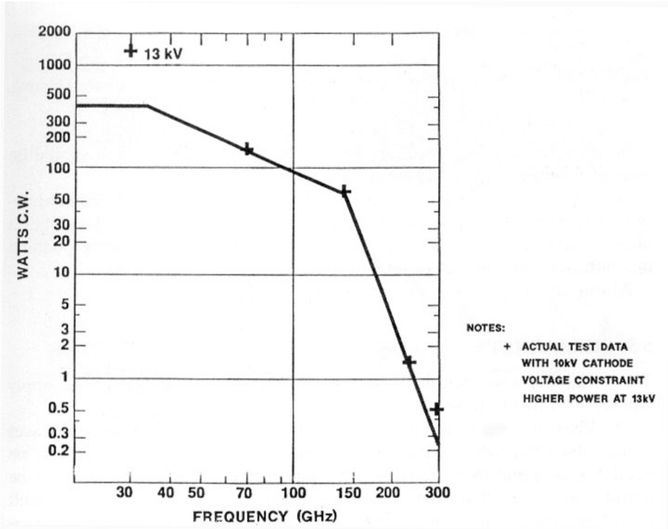

Figure 7/12: Measured data on Extended Interaction Klystrons (Reproduced from L. Sivan[24], 1994)

Power Output 1000 Watts (min)
Beam Voltage 11 kV (max)
Beam Current 1.05 A (max)
Frequency 27 to 35 GHz
1dB Bandwidth 100 MHz (min)
Saturated Gain 45 dB (min)
Cooling Method Liquid
Coolant Flow Rate 8 gpm (min)
Pressure Drop 50 psig (max)
Total Weight 35 lbs (max)
Size 9.2 x 7.5 dia. inches (max)

Figure 7/13: Commercial Extended Interaction Klystron developed at CPI and corresponding data.

The next microwave power tube that we will address is the Travelling Wave Tube (TWT). TWTs find a wide range of communication applications from electronic warfare (EW) to space exploration to the relaying of video signals. This is because no other device can rival the TWTs unique combination of bandwidth and gain. Moreover, with the advent of new technology and innovative concepts, the power and efficiency of the TWT have also been enhanced considerably. As an example, Figure 7/14 displays the increase of TWT power efficiencies during the last twenty years or so.

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[24] "Microwave Tube Transmitters", L. Sivan, Chapman & Hall, 1994

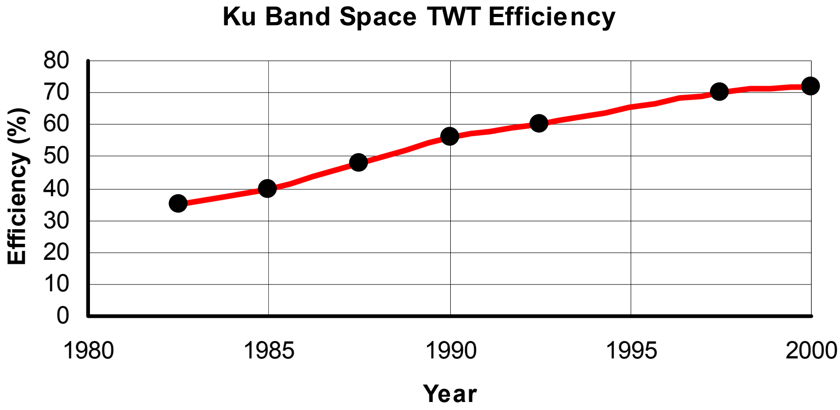


Figure 7/14: Increase in efficiency performance of Ku-band Space TWTs.

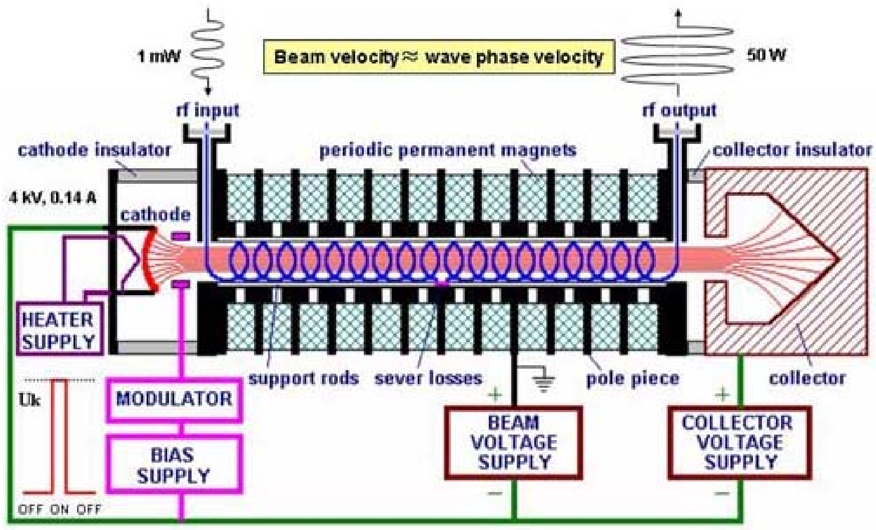
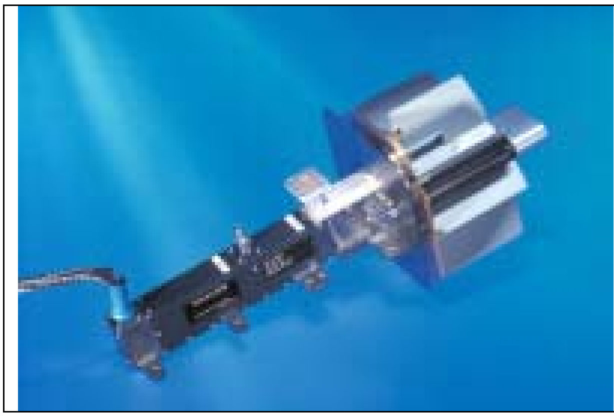


Figure 7/15: Schematic representation of the principle of operation of a helix TWT.

Figure 7/15 shows the principle of operation of a helix-TWT. An electron gun is used to produce a linear beam of electrons which are subsequently accelerated by the voltage difference between cathode and anode. Anode is circular and electrons flow trough it to be injected to the slow-wave interaction where they are confined with the use of a magnetic focusing structure. In this region, the beam interacts with a propagating electromagnetic wave. The propagation characteristics of the structure are such that the phase velocity of the electromagnetic wave is close to the electron drift velocity in the beam. Consequently, the kinetic energy of the electrons is transferred to the electromagnetic wave which is then amplified. The electrons, after their interaction with the wave, enter the collector region where their remaining kinetic energy is recovered by the depressed potential applied on the electrode of the collector.

Figure 7/16 to Figure 7/18 are showing some commercially available products in the Ka-band and up.



TH-4606 (Thales)

Frequency	***32 GHz***
CW Power	***30-35 W***
Efficiency	***53%***

Figure 7/16: TH-4606 TWT from Thales Electron Tubes and corresponding data. Note that this is Space-qualified equipment with a very high efficiency and radiating fans.

VTA-6430A2 (CPI)

Saturated Power Output	***500 watts***
Frequency (Voltage Tunable)	***28 to 30 GHz***
Efficiency	***> 30%***
Mass	***4kg***

Figure 7/17: VTA-6430A2 from CPI and corresponding data. Notice the high power/mass ratio of this device.

Miniature TWT

L-6024 (L3-Communications)

Frequency	***40-46 GHz***
CW Power	***40 W***
Mass	***700 g***

Figure 7/18: Miniature TWT. Reference L-6024 from L3-Communications and corresponding data.

Another type of TWT called folded waveguide TWT looks very promising[25]. The possibility of developing deep X-Ray lithography to produce precise synthesized structures is making it realistic to produce high efficiency high frequency devices, in large quantities. However, this technology is currently under development and should be first, carefully tested and improved.

Finally, let us mention the gyrotron. It is a relativistic beam interaction device which used a strong magnetic field to produce a helical electron beam that interacts with an electromagnetic beam in a drift space, producing wave amplification. MeV electron beams can be used, if high magnetic fields are used, making it possible to produce microwave power output in the megawatt range at frequencies well above 100 GHz. Of course using such a device in Space is very challenging, because it requires large superconducting magnets and very high voltages to operate. Fortunately, many different implementation of the principle of a gyrotron exist. Some of them allow for harmonics of the cryotron resonance to be used thus requiring much lower magnetic field and voltages to produce high power at 95GHz, from the amplification and non linear beam interaction multiplication of an input X-band signal[26]. Of course, developments of these gyro-TWTs are still being required to further improve and test the technology, but promising results can be expected in the next 10 years from now. These technologies would allow very high power CW coherent operation at very high millimeter frequencies. This could be advantageous in long distance wireless power beaming that we are interested in.

Finally, let us mention a very interesting direction of research currently underway, on Field Emission Array (FEA) and their use in the design of microelectronics millimeter vacuum tubes[27]. The main advantages of FEA are their high current density and transconductivity, and short electron transit time, in comparison with gridded thermionic cathodes all this leading to a possible increase in the operating frequency of emission-gated microwave devices.

As a conclusion to this review on microwave power generators, we should mention that microwave vacuum tubes are currently and for some other years again, the only viable technology for the high frequency and high power applications that we are interested in. TWT is certainly the best candidate for designs in the Ka-band. They are easily available and developments have been pushed to a limit in performance and quality while costs have gone down. At 60 GHz, klystrons are probably the best devices, but promising technologies emerge like folded-waveguide TWT and coupled-cavity TWT that could allow the fabrication of small and efficient, mass produced high power amplifiers at this frequency. If high frequencies and high power are required in Space, current status of the technology does not allow the use

[25] S. T. Han, J. I. Kim, and G. S. Park, "Design of Folded Waveguide Traveling-Wave Tube," Microwave and Optical Technology Letter (July 20, 2003).

[26] C.W. Baik, S.G. Jeon, D.H. Kim, and G.S. Park, "Frequency Multiplication in a Ka-band Harmonic Multiplying Two-Stage Tapered Gyrotron Traveling-Wave Tube Amplifier", International Conference on Infrared and Millimeter Wave(IRMMW), Sep. 28-02, 2003 (Otsu, Japan)

[27] A. G. Rozhnev, N. M. Ryskin, D. V. Sokolov and D. I. Trubetskov (SSU), S. T. Han, J. I. Kim and G. S. Park (SNU) "Novel Concepts of Vacuum Microelectronic Microwave Devices with Field Emitter Cathode Arrays " Physics of Plasma, Vol. 9, No. 9, pp. 4020-4027, September 2002

of gyrotrons but new designs and solutions are emerging using non linear electrodynamics harmonic multiplying like in gyro-TWTs. They would allow the use of lower magnetic fields and could lead to practical solutions for Space applications.

7.4.2 Rectennas

A rectenna (rectifying antenna) consists in a collecting antenna attached to a rectifying circuit that aims at converting the incoming microwave power into a DC electric power.

Figure 7/19 shows a conventional schematic representation of a rectenna exhibiting the different blocks that constitute the rectenna. The antenna collects the power from the incoming microwave beam. The input filter matches the impedance of the antenna to the one of the diode. On course, the diode being a non linear circuit, this match is taken at fundamental frequency. At harmonic frequencies of the fundamental operating frequency, the filter is usually equivalent to a short circuit which filters the higher harmonics that may be generated at the non linear Schottky diode, preventing them from being radiated back by the antenna.

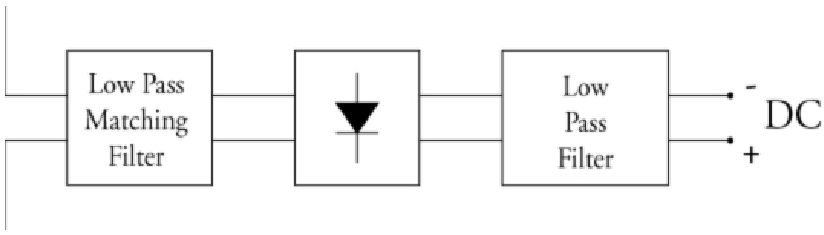


Figure 7/19: Schematic representation of the general structure of a rectenna

Because the diode circuit is non linear, such a matching can only be obtained at a given input power and frequency. This matching is also very much dependant of the operating point which is dependant on the output load. This means that efficiency is generally optimum only for a given load value at the frequency and input power for which it has been designed. Consequently, this imposes constraints on the way that one can connect an array of rectenna together to supply power to a single load. The series or parallel connection and the value of the load must be chosen so that each rectenna operates close to its optimum. This can only be achieved if the power density is nominal. On large rectenna arrays, illumination may not be uniform and finding the best way of connecting together rectennas so that the overall efficiency of the system stays high is a difficult task. In the applications considered in this study, and because of the reasons already presented in the first section of this document, power density over the entire surface of the rectenna array can be considered constant. This makes the problem of connecting the rectennas together much easier. Power density at the rectenna aperture may change between an upper limit and a lower limit, which will be considered as the operating range of the system outside of which the system cannot work. This involves that a system must exist to adapt the load in order to get the maximum power out of the system at any time. Finally, other requirements exist for the rectenna array. It must be light and possibly be initially packaged in a small volume for its launch and transport to Mars. Compared to the problem of building vast areas of rectenna arrays on the Earth surface to get power from Space, our applications do not necessitate the development of an industrial fabrication process, only few pieces will be needed and only small array surfaces are considered for such applications. Perhaps only the delivery of power to a base on Mars may require the use of a relatively large rectenna, and solutions will have to be found for the packaging and deployment of such an array on Mars.

The highest efficiency rectenna ever proposed was developed by W.C Brown at Raytheon, in 1977[28]. Brown used a GaAs-Pt Schottky diode and obtained a 90.6% efficiency at an input power level of 8 W. At 5.8GHz, greater than 80% efficiencies were reported[29]. At 35GHz, 72% RF to DC conversion efficiency was measured[30], although it was earlier noticed that low efficiency is generally expected from GaAs Schottky diodes at these frequencies. In order to get better efficiencies at 35GHz or above, higher cutoff frequency materials should be used. SiGe might be a possible material for Schottky diodes at these frequencies. This of course would lead to expensive devices, but for the applications foreseen in this study, no large array is needed and the total cost of diodes does not constitute the most critical point.

To conclude, let us mention that rectenna could very much benefit from the research on active antennas. Indeed, the antenna could play the role of collecting the energy with a maximum gain, while filtering higher harmonics and thus realize a multi-harmonic tuning that allows the conversion by the diode of a maximum amount of microwave power into DC. This could lead to much more compact designs. Many designs being dedicated to the collection of power on Earth, have concentrated on reducing spurious from being radiated back at unpredictable directions. Some of them advocate the placement of the rectifying circuit below the ground plane[31]. This effectively decouples the RF portion of the circuit from the DC lines and reducing the possibility of harmonics to be fed back to the antenna. For applications in Space with distance separating the collecting unit from any other electronic system, the reradiated harmonics would only have a minor effect and do not represent a real issue. Consequently, this could yield to simpler designs and hopefully decrease the weight and cost of the system. Filtering should only be optimized so as to allow for the maximum efficiency of the system, eventually in a large range of input power.

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[28] W.C. Brown, "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system", Raytheon Company, Wayland, MA, Tech. Rep. PT-4964, Nasa Rep. CR-135 194, Aug. 1977.

[29] J.O. McSpadden, L. Fan and K. Chang, "Design and Experiments of a High-Conversion-Efficiency 5.8GHz Rectenna", IEEE Trans. On Microwave Theory and Techniques, Vol. 46, N°.12, December 1998, pp.2053-2059.

[30] P. Koert and J.T. Cha, "35GHz Rectenna Development", in WPT-93: First Annual Wireless Power Transmission Conference, Center for Space Power, Texas A&M University, College Station, Texas, pp. 457-466, 1993

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7.5 MICROWAVE BEAM STEERING AND FOCUSING

This section addresses the most critical technical aspect of microwave WPT systems for large distances in Space, the one of a reliable control of the beam focusing and direction, so that most of the beam energy is focused on the collecting antenna target.

All the applications for remote provision of energy to Space exploration systems, are considering a movement of the target collecting unit relative to the projecting SPS or the contrary. This movement can be a planned orbital trajectory of an SPS system beaming power to a fixed position on the surface of a Planet. It could also be a random path of a rover exploring the surface on Mars or the Moon. This latter case, prohibits the use of planning beam steering where at each point in time would correspond a known and planned beam angle and consequently an attitude of the satellite or a phase and amplitude distribution of the microwave feeding signal over the projecting array. Furthermore, such a planning would be difficult to achieve, because some effects are unpredictable, like multi-paths formation and angle of sight change do to atmospheric diffraction effects on Mars.

Consequently, what we are looking for is an adaptative beam control system. There are two way of coping with this problem. The first is to find a way for the SPS to know at each point in time, the position of the collecting target. Assuming the geometry of the projecting antenna is known, mechanical correction can be made to it pointing or, if an electronic phased-array steering system is used, the correct phase and amplitude distribution of feeding signals can be synthesized from this known data. Finding the direction is a known problem. Direction finding space domain filtering algorithms (MUSIC or ESPRIT) can be implemented on a sensing phased-array, with perhaps enough precision for the problem at hand. Such technique would imply that a beacon signal is emitted from the target collecting system and be detected by the sensing array. Coding of this signal could even be used which could on one hand, to avoid detecting false targets or interferers, and on the other hand, allow for multiple targets to exist and allow the implement of a time multiplexing for the delivery of power to these different targets.

There are unfortunately various points that make this solution difficult to implement. First, array-feeding synthesis algorithm, usually assume the geometry of the emitting array to be constant and well known. This cannot be the case of large arrays in Space. Indeed, vibration and gravity variations would lead to twisting and bending of the structure and consequently would cause the solution given by these array-feeding synthesis algorithms to be inadequate, generally leading to a spreading of the energy of the main beam and to higher secondary lobes. Second, the algorithm would need to account for the beam deviation that could occur during the beam path through the atmosphere. Finally, if the drifting speed of the SPS relative to the collecting target is high, one has to be certain that the time separating the determination of the target direction and the establishment of the corrected phase distribution is short enough so as not to always miss the target.

The key points addressed in the following paragraph are to be analyzed for the application cases that we are interested in, and more particularly these applications which can take profit of using microwaves for the transport of the power to the target. For example, applications which consist in beaming power to rovers or base station on the Moon, do not suffer from the beam deviation problem. On the other hand, distances being very high, we would need to use millimeter frequencies to reduce the size of the projecting and collecting systems. At these frequencies, even minor phased-array plane deformations are critical, because they do not represent a perturbation but really a large phase rotation, which could definitely change the radiation characteristics of the array. This is very difficult to cope with array-feeding synthesis techniques.

To alleviate these problems, many SPS designs have advocated the use of retro-directive phased-array projecting antenna[32, 33]. In such systems, a pilot signal is emitted from the center of the collecting target antenna. This pilot signal produces a phase front at the projecting antenna level, which is deformed by the perturbation caused by the propagating media. This phase front is sensed at each time by the projecting array sensors. The phase information of the incoming phase front at each sensor is conjugated. The conjugated phase signal is used to control the phase of the output signal at each radiating element of the array. This causes the projected microwave power beam to follow the path followed by the pilot signal, but in reverse direction, making the beam hit the target collecting antenna at any time.

This technique insures that the phase of the radiated RF power signal of each radiating element is automatically varied in the proper amount, as the array is subjected to both mechanically and electrically induced RF pathlength or phase changes.

In order to reduce the complexity and the cost associated to phase conjugating networks, designs of large projecting arrays generally involve the use of subarrays. Only one sensor is available at each subarray to measure the pilot signal's phase value at the subarray and conjugate it to provide the same conjugate phase signal to each radiating element of the subarray. Subarrays are subject to possible angular tilt from the reference average plane of the array due to backup structure deflections. Previous studies and SPS system architecture have determined the effect of global antenna tilt and subarray tilt. Subarray tilt mainly affects the amount of scattered power from the main beam, while antenna tilt determines the power in the grating lobes. An antenna tilt and subarray tilt budget has to be made for each application scenario to provide an insight of what is the optimum value of subarray size and spacing to allow for acceptable performance deterioration.

A recent paper on the development of a retro-directive control transmitter, by F. Little et al.[34], comes back on these considerations in the case of reference studies of SPS architectures developed recently at Nasa, and builds on this tilt budget analysis and grating lobe characteristics to derive an optimum subarray size. The subarray is subsequently designed and was demonstrated at the IAC congress in Houston, in 2002. Other demonstrations have already been presented of this technology in past years, although much work

32 N. Kaya, « A New Concept of SPS With a Power Generator/Transmitter of a Sandwich Structure and a Large Solar Collector », Space Energy and Transportation, Vol. 1, N° 3, 1996, pp. 205-213

33 W.C. Brown, "Development of Electronically Steerable Phased Array Module (ESPAM) with Magnetron Directional Amplifier (MDA) Power Source", Final Report, Microwave Power Systems, Weston, MA, Texas A&M Research Foundation Subgrant N° L300060, Project RF-2500-95, Sept. 1995

34 F.Little, personnal communication. Work submitted to the 2004 URSI conference in Kyoto.

has yet to be undertaken to demonstrate the robustness of this technology in front of interfering signal, multiple paths of the pilot signal due to reflections on surrounding spacecrafts or systems and how this technology can be combined with a control in the amplitude distribution of array to provide better performance and less crucial thermal management issues.

There has also been no demonstration of this technology at millimeter frequencies and such realization looks very challenging. Indeed, small array plane deformation at these frequencies would imply large phase rotation. This requires the use of fast analog phase shifters and probably, the bandwidth of microwave tubes must be large enough to linearly amplify the fast phase shift of the driving signals.

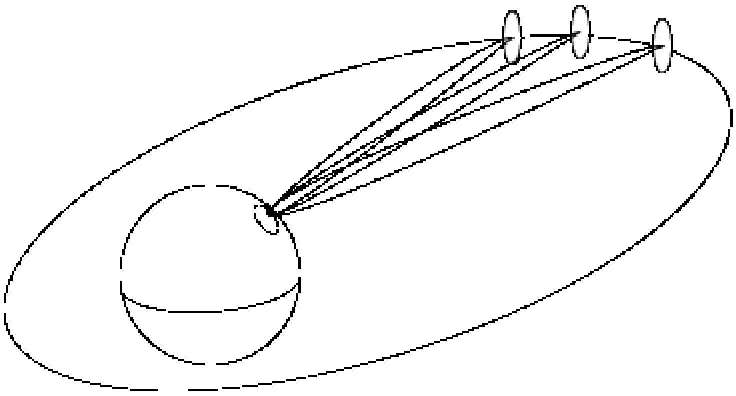

Figure 7/20: Schematic representation of fleet sparse array.

The applications to provide energy to Space exploration and other systems in Space are usually long distance applications. Furthermore, the target utilization cannot usually afford the use of large collecting rectenna arrays. This supposes that a large projecting antenna be used if most of the projected power needs to be captured at the collecting antenna and this also advocates for the use of high frequencies, as already discussed in this document. Deploying large structures in Space for beaming power to large stations on the Earth's surface is difficult because investments return times cannot be kept short enough and because of other technological and environmental hurdles. Doing the same for provision of energy in Space does not alleviate the problem. One has to find a way to artificially increase the gain of the projecting antenna, while not increasing having to build large structures in Space. The idea would be to use several average size projecting arrays on board spacecrafts that would form a fleet and coherently beam power towards the target antenna (Figure 7/20). Of course, subarray separation would cause grating lobes to be closer to the main beam. However, amplitude control could lower the intensity of these grating lobes. Grating lobes are not so important for example in the Mars environment in the absence of critical communication systems and life maintenance systems. Much of the systems in this environment would also be protected against high power densities at the chosen WPT frequency. Using such sparse arrays should enable high power densities to be present at the rectenna section to ensure an optimum operation of the rectenna and deliver the required amount of power.

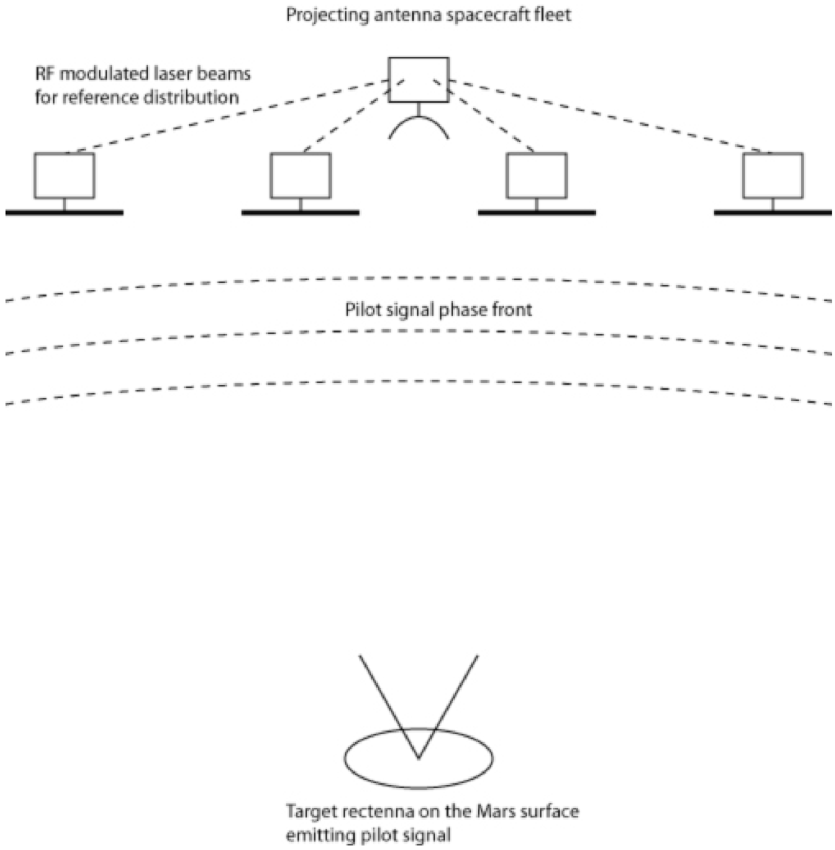

Figure 7/21: Schematic representation of a spacecraft projecting antenna fleet. Phase reference is distributed to each spacecraft by an RF modulated laser beam. Fleet geometry is kept constant allowing for calibrating of the system.

Such an approach, however, requires a phase reference to be distributed between the spacecrafts in the fleet. This could be achieved using RF modulated lasers. Distances separating Spacecraft in the fleet can be maintained almost constant using laser positioning systems. This insures that constant phase difference exist in the optically distributed RF phase reference, which can be calibrated and corrected for at periodic intervals in time.

Using such fleet formation arrays in the Earth environment or to deliver power to a communication platform on GEO is not practical because of the large grating lobes. This is why it is believed that if such a solution can be realized, it should be dedicated to power beaming on Mars or to cases where such grating lobes could not interfere with other vital equipments.

Of course, more work has to be done to validate this proposal. Basic calculations are underway and simulations should be performed to estimate the performance of this system and its ability to provide the required amount of energy to the target collecting rectenna arrays on the Mars surface. A tradeoff study needs to be performed to compare this approach and its cost to other solutions and determine the viability of this proposition.

As a conclusion, previous studies on large projecting antenna arrays have demonstrated theoretically that reliable beam steering could be realized using phase conjugating retro-directive antenna arrays. Deploying such large structures for provision of small amount of energy may not be desirable. A solution is proposed but not demonstrated to use a constant geometry fleet of spacecrafts orbiting on the same Mars GEO orbit. Phase reference is provided using RF modulated laser beams from a reference spacecraft. Retro-directive phase conjugation is then possible. Closer grating lobes are expected from this configuration and higher level sidelobes but the gain in the main lobe is also increased, making it possible to provide de required amount of energy the target utilization.

8 SYNTHESIS

A review of the main elements of the Space power delivery system has been made.

For power collection, which has to provide very high level of power (order of MW and beyond), solar array with small concentrator and thermal generator (Stirling system) have been retained. Both should be assessed with respect to the different mission case and the mass and cost points of view.

The electrical power distribution to the power beam generator has to be analysed; in particular, high voltage bus (typically 1000 V) will be considered to limit the high value of the current to manageable value.

Several options have been reviewed for the laser based power transmission system. Single space based laser will be limited to diameter in the range of 30 m. To have larger aperture, a constellation of free-flying telescopes is proposed, with the problem of maintaining relative distance between the satellites with a very high accuracy. The constellation is useful for high emitted power or for very long distances.

The retained laser power technologies are the CW Nd-Yag laser and the CO2 laser. The first one operates in the sunlight wavelength. It could be pumped by laser diode or by solar radiation. The receiver system could be an optimised PV cell. The CO2 laser shall be associated with a thermal generator (Stirling machine for instance) as receiver system.

Several frequencies have been assessed for the RF based power transmission system. The selection will depend on the technologies available for beam generator and receiver system and of their performances in term of efficiency. A compromise has been found around 35 GHz, or below. The selection will depend on criteria such as overall performance of the system, impact on the target, mass of the SPS, etc. As compared to the Space-to-Earth systems, the size of the receiver system (rectenna or other) is constrained by the impact on the user (target), which could be a satellite, or a small element on a planet. Assessment of the RF system will depend on the mission cases.

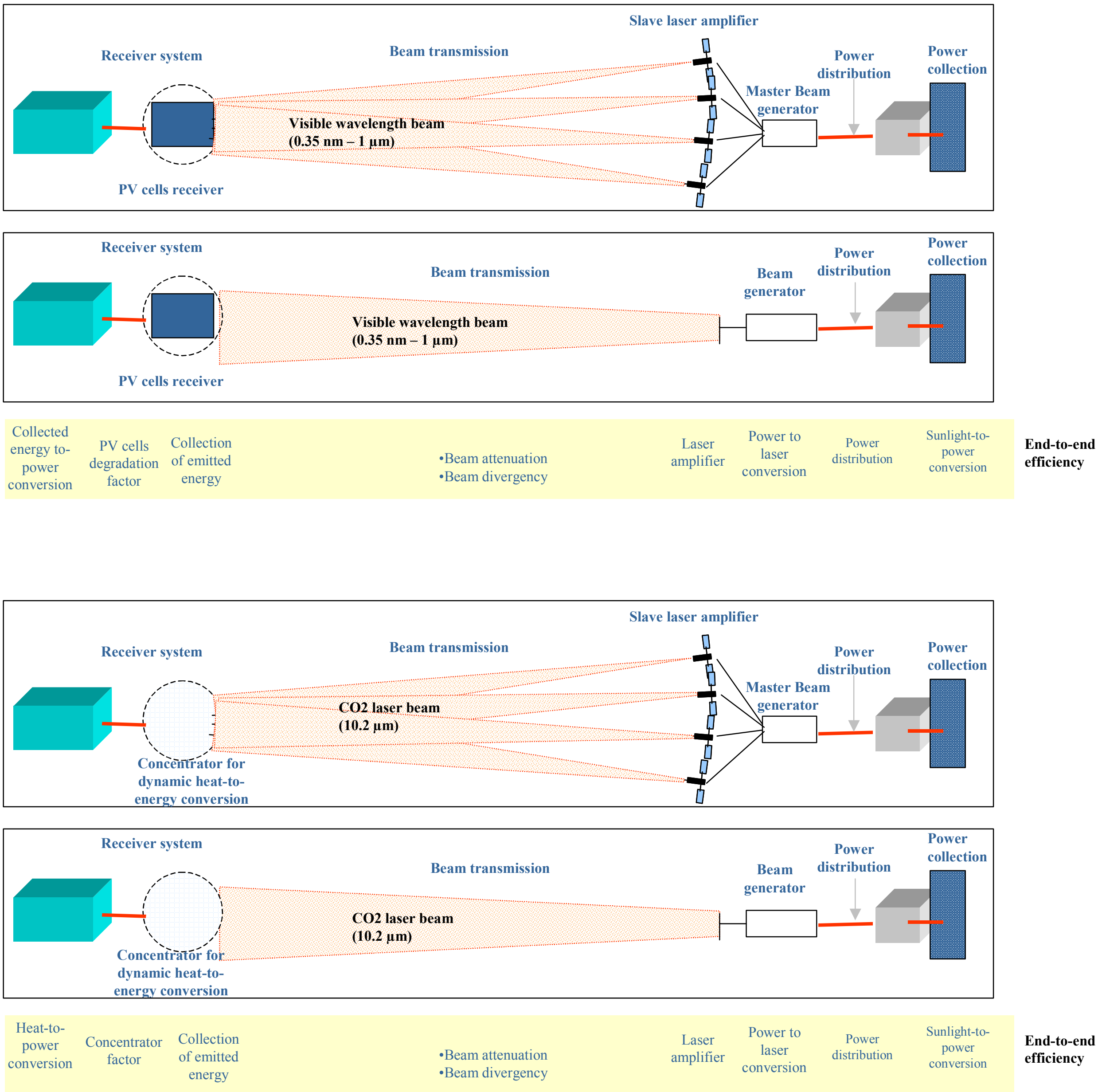

Figure 7/1: Summary of the candidate laser power transmission systems

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