TAS Astro
Satellite Electrical Systems

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DEFENCE AND SPACE

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About the presenter

- **Nicolas Neugnot**
  Power systems manager and senior expert

- **Contact**
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- **Experience at Airbus Defence and Space**
  - Power system sizing and power unit procurement
  - Electrical and power system engineering team leader
  - Responsible for electrical power systems in Space Systems Engineering
  - Power systems expert
- **Current activities in Airbus Defence and Space**
  - Define power system roadmap
  - Lead new development
  - Manage improvements and standardisation
- **Education:**
  - Graduated in Ecole Nationale Supérieure d'Electricité et de Mécanique de Nancy in France

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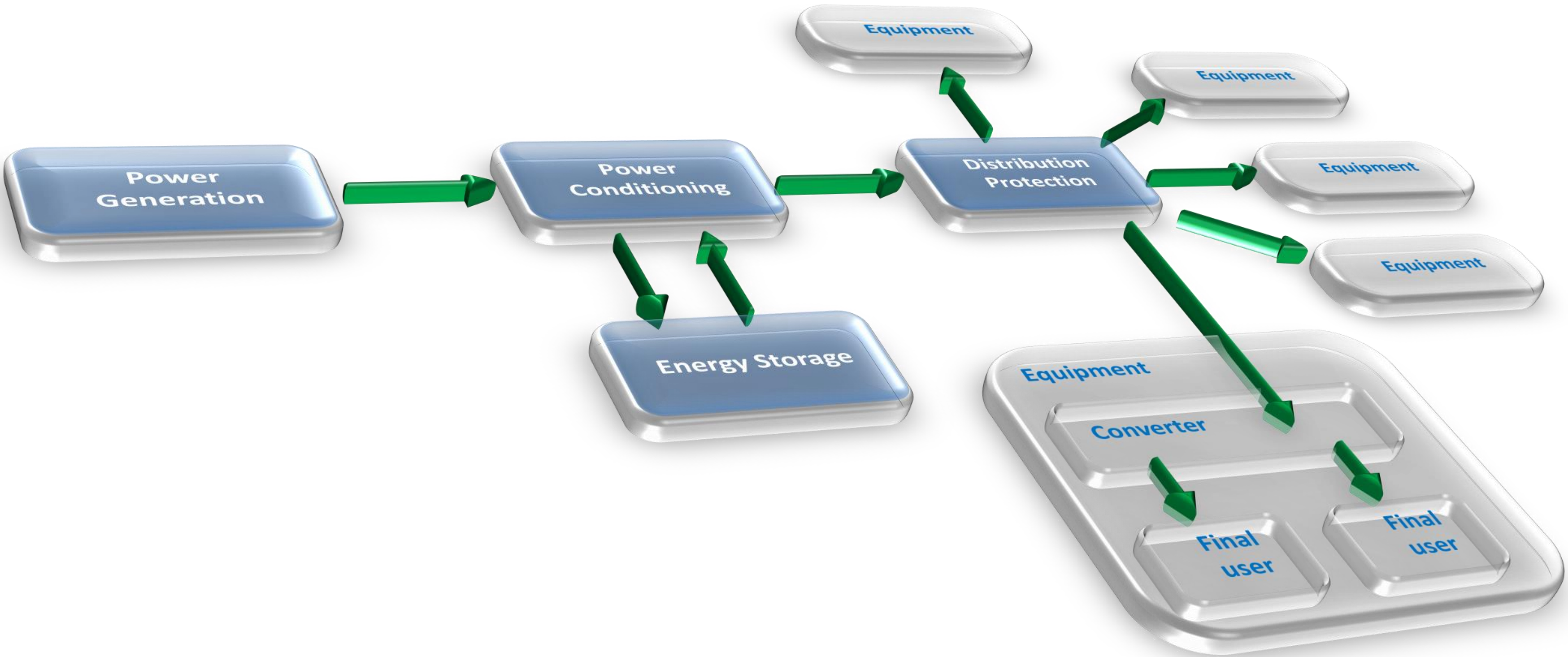
What are we talking about an electrical power system?



TAS Astro - Satellite Electrical Systems

First Day:	**Introduction, Space constraints and Power Generation**
	Nicolas Neugnot
Second Day:	**Energy Storage**
	Marc Sabathé
Third Day:	**Electrical Architectures**
	Laurent Gajewski
Fourth Day:	**Evaluation**
	- Quiz
	- Satellite Electrical System sizing

What are your expectations?

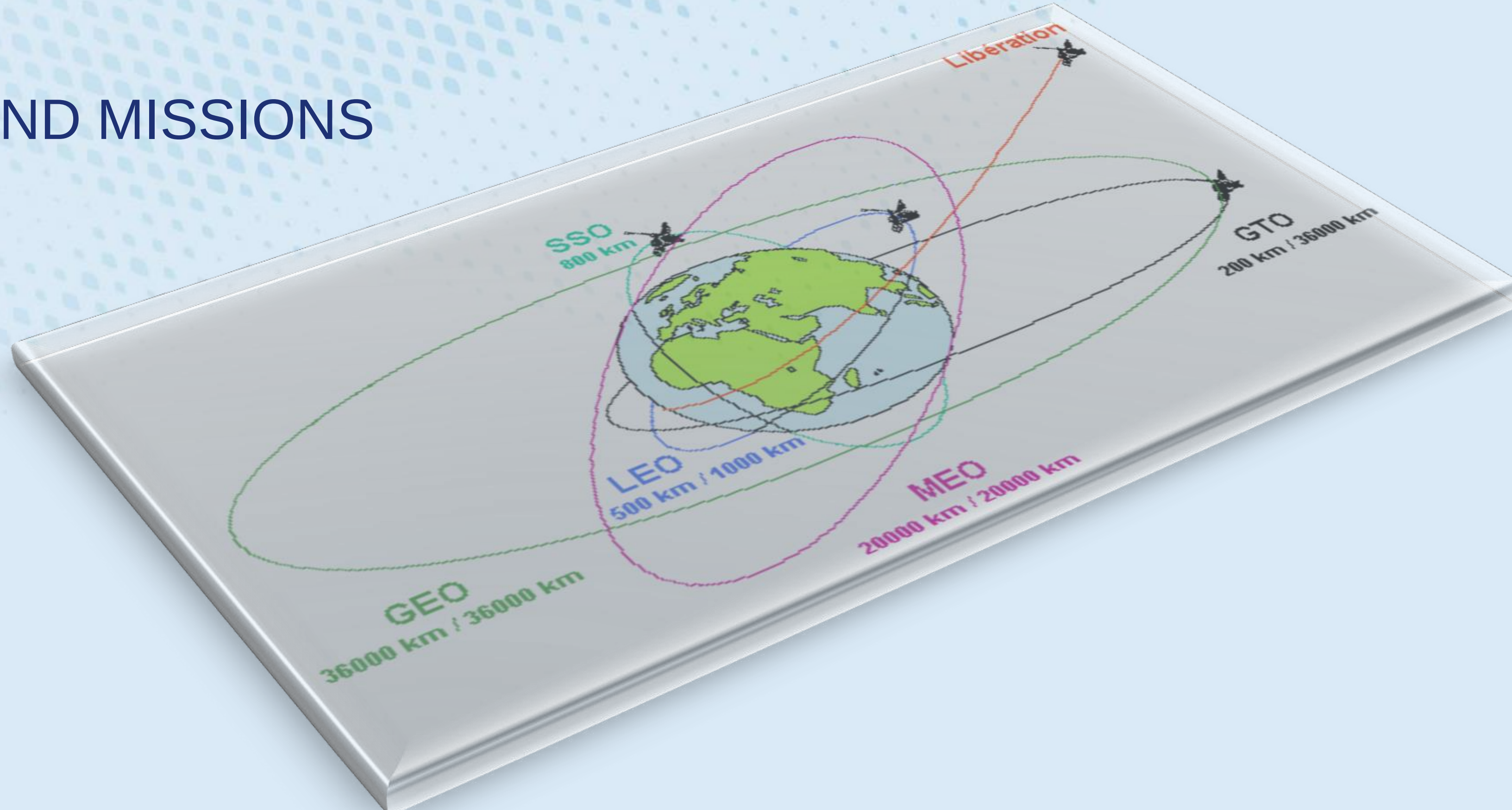
Agenda for today

9:00 – 10:00	**Introduction & Space constraints** – Type of missions: the importance of the orbit – Space environmental constraints
10:00 – 10:15	**Coffee break**
10:15 – 11:15	**Power Generation in Space** – How to generate power in Space? – Solar cells technologies
11:15 – 11:30	**Coffee break**
11:30 – 12:30	**Power Generation in Space** – Solar array design

Acronyms

AC	Alternating Current	GEO	Geostationary Earth Orbit
AM	Air Mass	GTO	Geostationary Transfer Orbit
ANLH	Ascending Node Local Hour	HiEta	High Efficiency
AOCS	Attitude and Orbit Control System	Im	Current at maximum power
APU	Auxiliary Power Unit	Isc	Short Circuit Current
ARC	Anti-Reflective Coating	ISS	International Space Station
aSi	Amorphous Silicon	JPL	Jet Propulsion Laboratory
AU	Astronomical Unit	LEO	Low Earh Orbit
BCR	Battery Charge Regulator	Li-ion	Lithium Ion
BDR	Battery Discharge Regulator	LILT	Low Intensity Low Temperature
BOE	Beginning Of Eclipse	LISN	Line Impedance Simulation Network
BOL	Beginning Of Life	MEO	Medium Earth Orbit
BSF	Back Surface Field	NiCd	Nickel Cadmium
BSFR	Back Surface Field and Reflector	NiH2	Nickel Hydrogen
BSR	Back Surface Reflector	PCB	Printed Circuit Board
CE	Conducted Emission	Pmax	Maximum Power
CFRP	Carbon Fibre Reinforced Plastic	PSA	Part Stress Analysis
CS	Conducted Susceptibility	PWM	Pulse Width Modulation
CV	Converter	RTG	Radioisotopic Thermal Generator
DC	Direct Current	S3R	Sequential Switching Shunt (or Series) Regulator
DJ	Double Junction	SA	Solar Array
DOD	Depth Of Discharge	SADM	Solar Array Drive Mechanism
EMC	ElectroMgnatic Compatibility	SCA	Solar Cell Assembly
EOC	End Of Charge	Si	Silicon
EOD	End Of Discharge	SOA	Safe Operating Area
EOE	End Of Eclipse	SOC	State Of Charge
EOL	End Of Life	SSO	Sun Synchronous Orbit
EPS	Electrical Power System	SSPC	Solid State Power Controler
ESD	ElectroStatic Discharge	TJ	Triple Junction
FET	Field Effect Transistor	UVD	Under Voltage Detection
FF	Fill Factor	Vm	Voltage at maximum power
GaAs	Gallium Arsenide	Voc	Open Circuit Voltage

ORBITS AND MISSIONS



Orbit, a major driver for electrical power systems

Selected by the mission, the orbit drives the spacecraft design

SPOT-4 : Sun-synchronous

INTELSAT-X : Geostationary

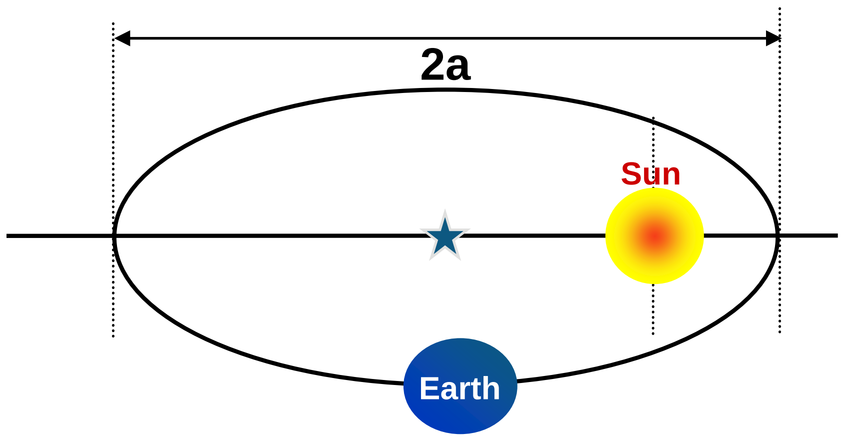
Orbital mechanics: 3 Kepler laws

1609 : - The trajectories of planets around the Sun are in a plane and elliptical.

1609 : - Their radius describe surfaces proportional to the time

1619 : - There is a relation between the semi major axis and the orbital period:

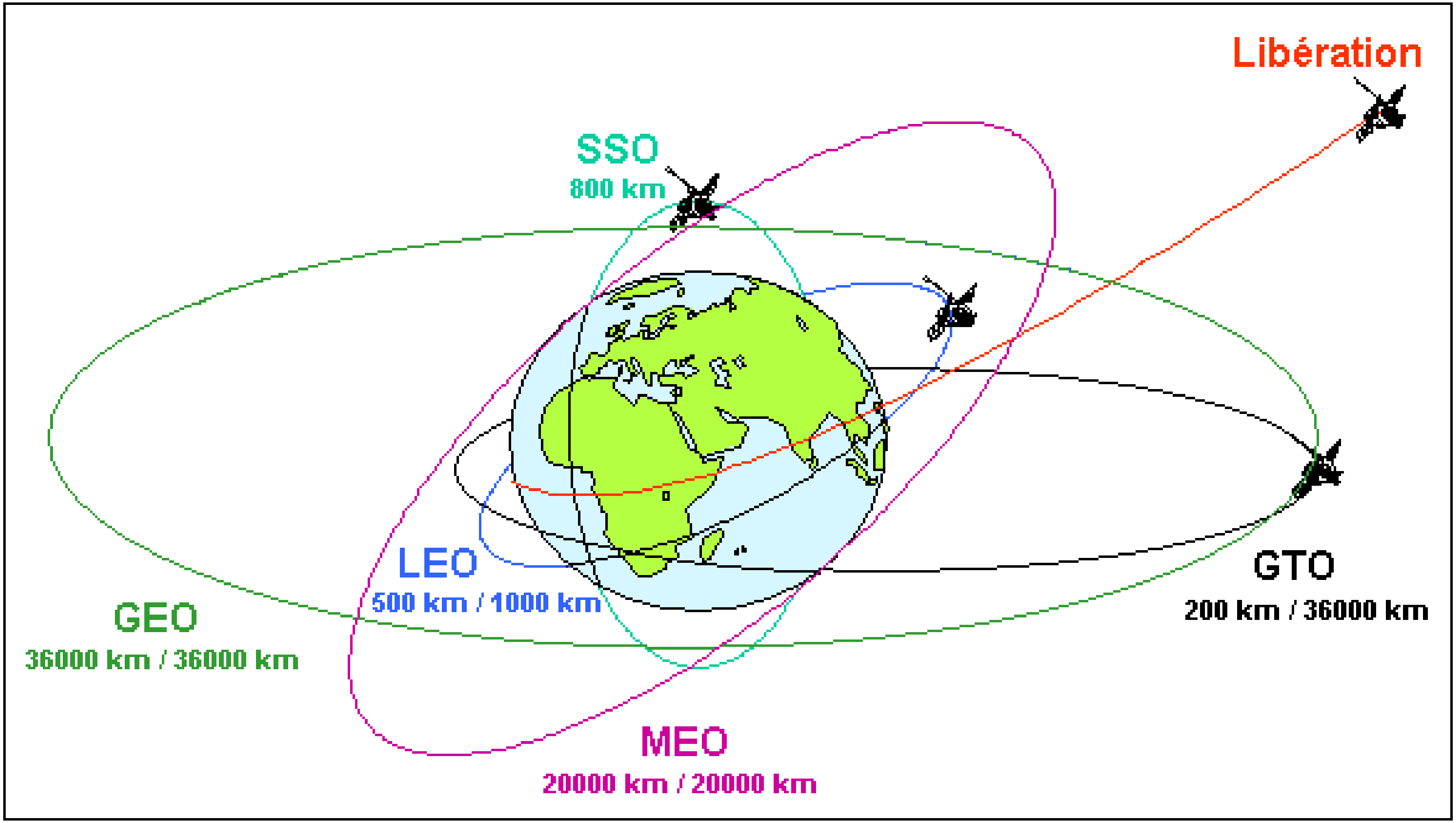
$$\frac{T^2}{a^3} = cste$$



1687 : Newton gravitational law

$$F = \frac{GMM'}{d^2}$$

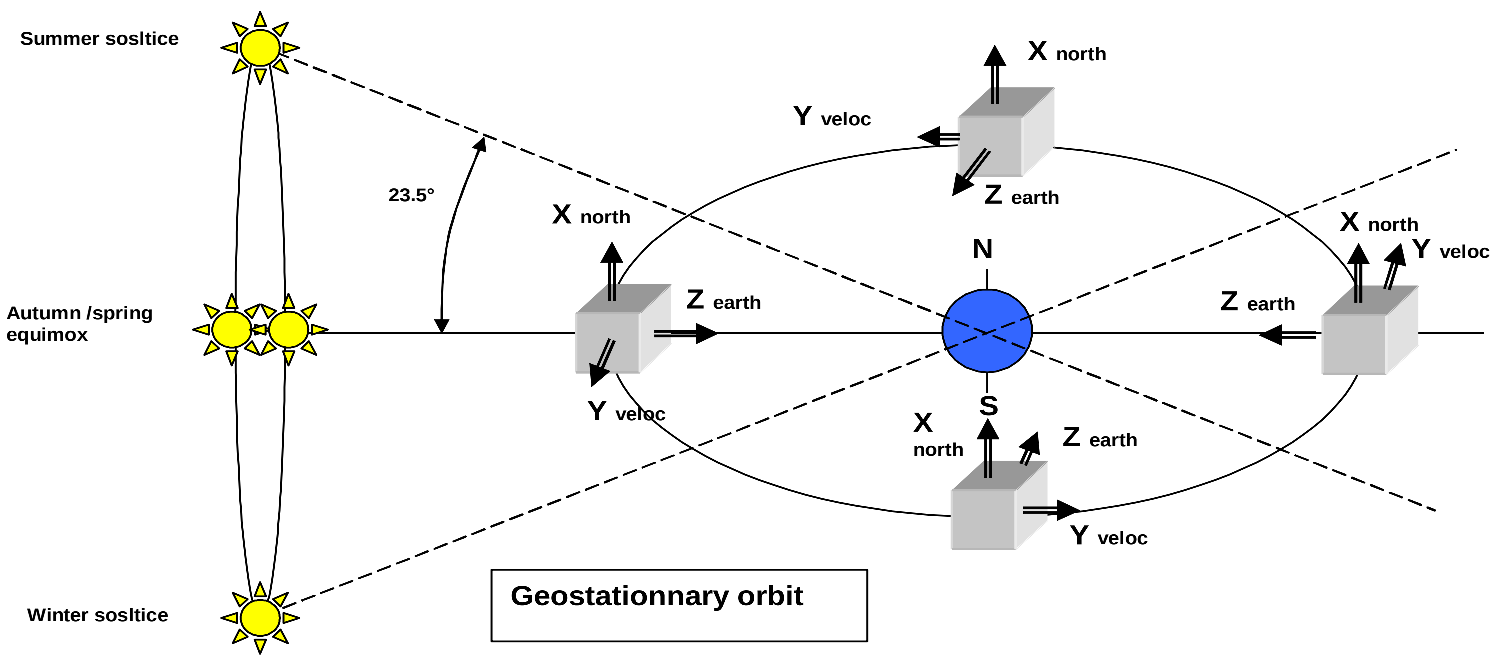
Type of orbits



Geostationary orbit

Used for **telecommunication and meteorological** missions requiring a global coverage

- **Parameters:**
  - **Altitude: 35786 km**
  - **Period: 24h**
  - **Elevation: 0° (equatorial plane)**
  - **Circular orbit**
  - **Satellite pointing: geocentric**



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Geostationary orbit

It impacts **thermal exchanges and eclipse regime**

+X and –X sides are less exposed to Sun

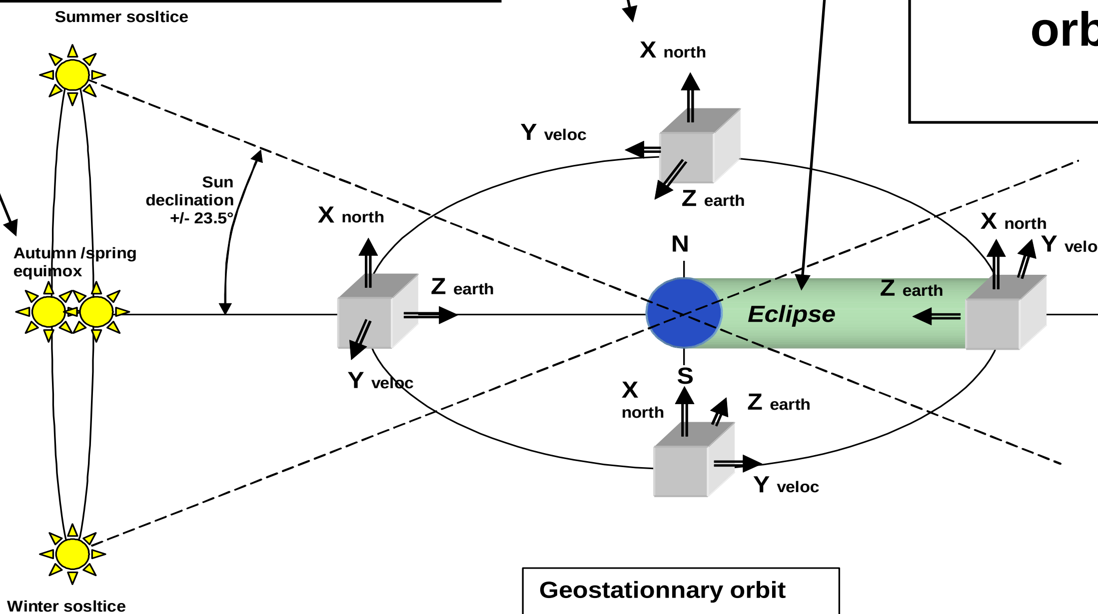
→ used for heat rejection

Eclipse occurrence is low due to Sun declination

Eclipses have a low duration versus orbit period

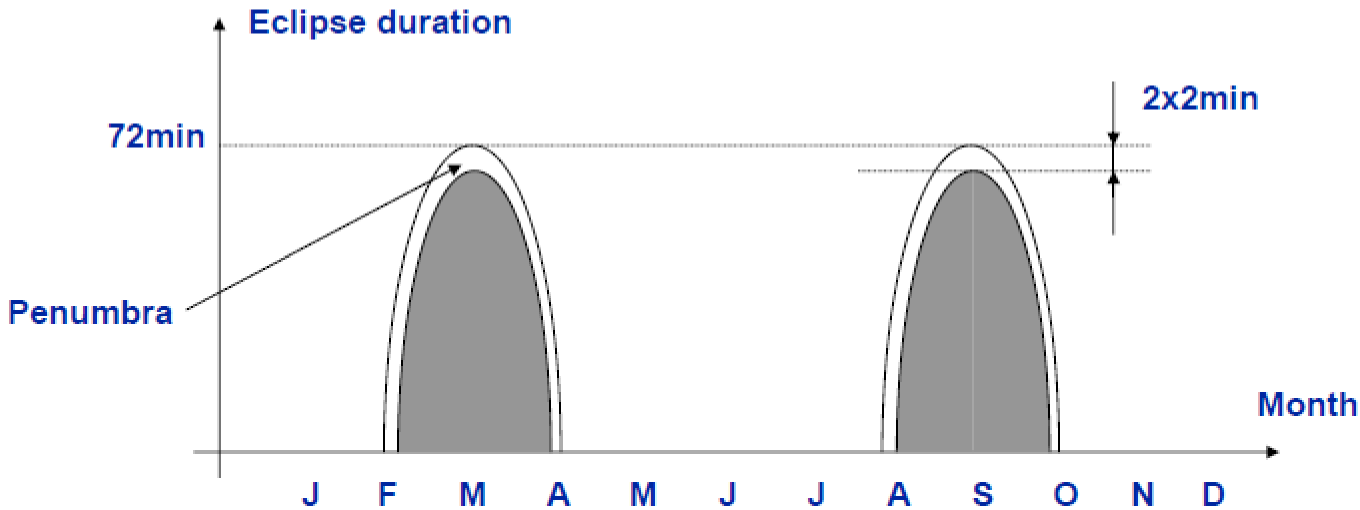
Solar flux is main contributor

Earth and albedo can be neglected (due to the high altitude)



Geostationnary orbit

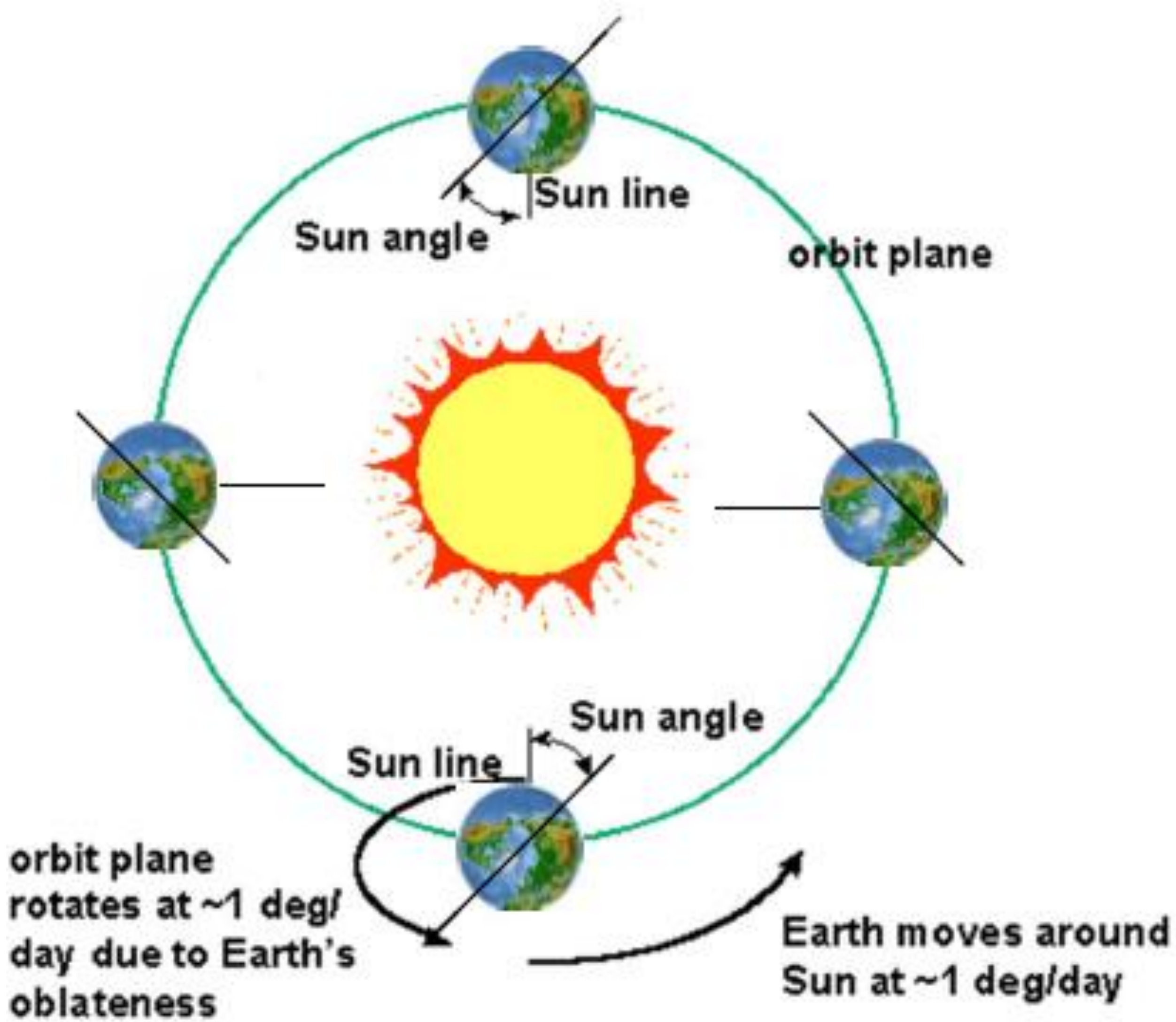
Geostationary orbit



Eclipse:

- **Seasonal effect**: occurs only 2 x 45 days per year, when sun is close to equinox (i.e. sun close to equatorial plane), i.e. sun declination in the range [-8.7°, +8.7°]
- The duration of the eclipse depends on the sun declination, with a **maximum of 72 minutes compared to 24 orbit period**

Sun-synchronous orbit



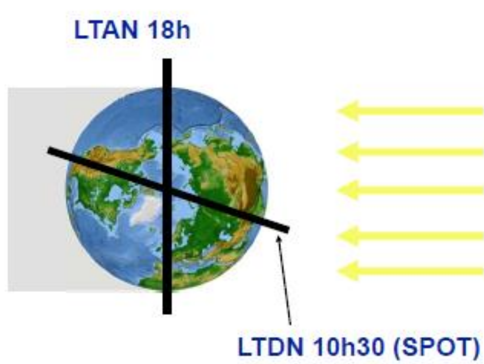
Sun-synchronous orbit

Earth oblatness is responsible for a rotation of the orbit plane

- negative (i.e. reverse to Earth rotation) function of inclination i, $0° < i < 90°$, expressed as $-0.58(R/(R+h))^2\cos(i)$ degree per rotation
- positive for $i > 90°$, this ensures **sun-synchronism**, i.e. to maintain a constant angle between orbital plane and Sun direction

A major parameter of a Sun synchronous orbit is the **Local Time of Ascending Node (LTAN)**

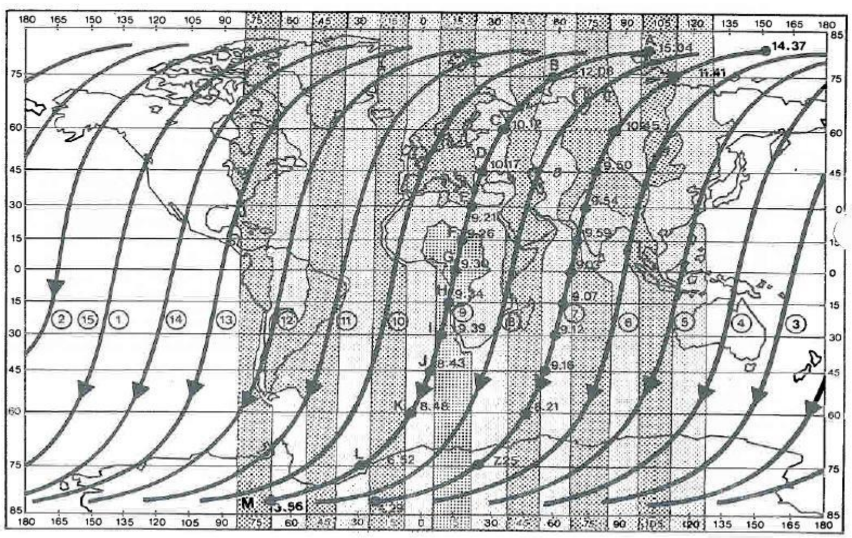
- 6 a.m. or 6 p.m. LTAN may allow, for high enough an orbit, to never experiment eclipses
- Conversely, for a LTAN close to 12 a.m. or 12 p.m., an eclipse is met at each orbit



Sun-synchronous orbit

Used for **Earth observation** missions → offers a good coverage of the Earth (about 14 tracks every day)

- **Parameters:**
  - **Altitude: 400 to 800 km**
  - **Period: about 100 minutes**
  - **Elevation: close to 90° (polar)**
  - **Circular orbit**
  - **Satellite pointing: geocentric during imaging, helio-centric else**



Sun-synchronous orbit

Sun-synchronous orbit

It impacts **thermal exchanges and eclipse regime**

« anti-Sun » side is always prevented from the Sun

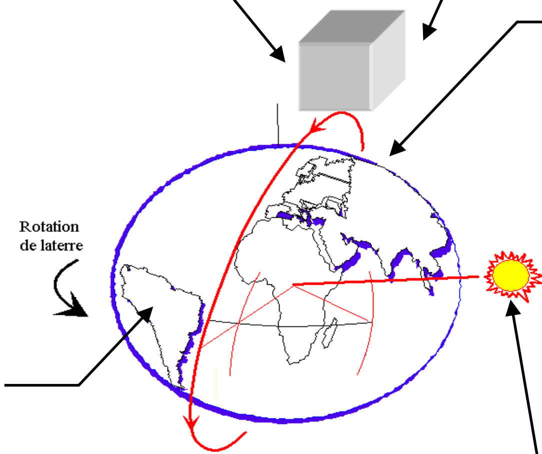
→ used for heat rejection or even cryogenic cooling (typ.-100°C)

Eclipse occurrence is 100%

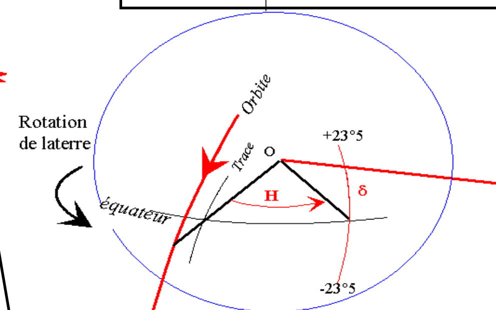
Eclipse duration is about 30 % (i.e. 33 min/100 min orbit)

Sun side → used for power generation

Orbit inclination v.s. Sun is constant (ascending node)



Orbite héliosynchrone SPOT
Altitude 822 km
Inclinaison 98°7
Heure solaire au noeud descendant 10 H 30



δ = Déclinaison solaire
H = Angle horaire au noeud ascendant

All fluxes (solar, albedo, earth) and significant, none can be neglected

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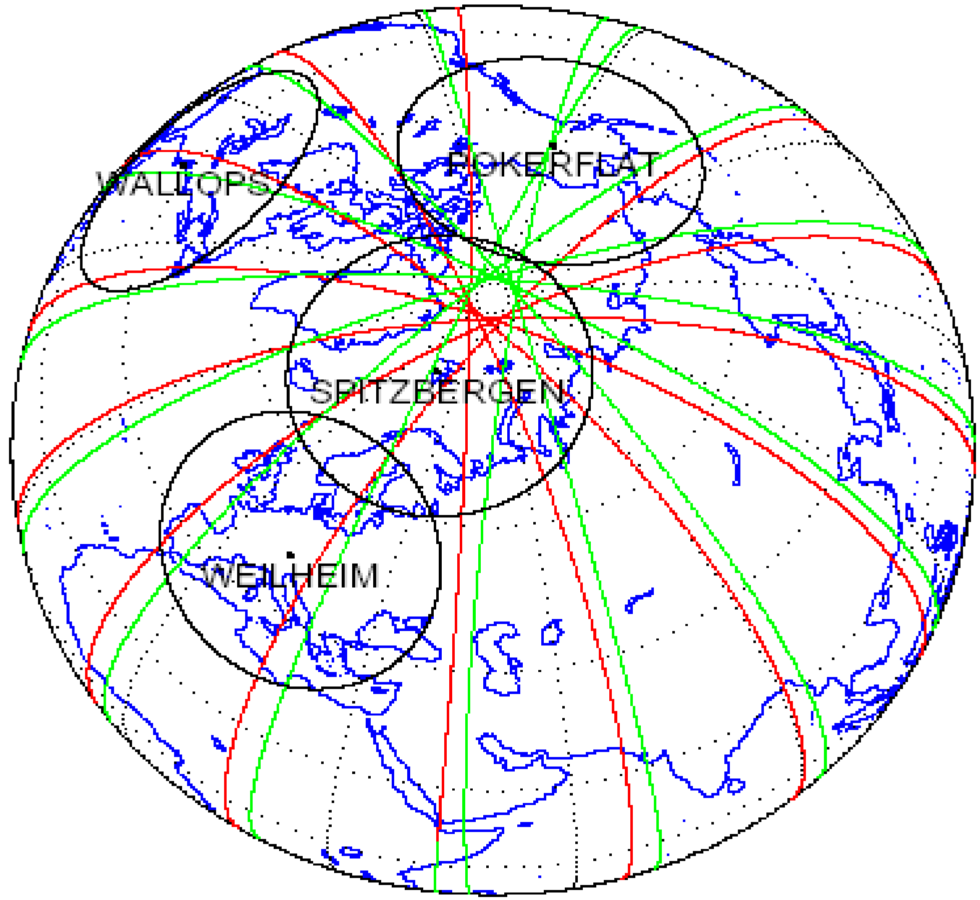
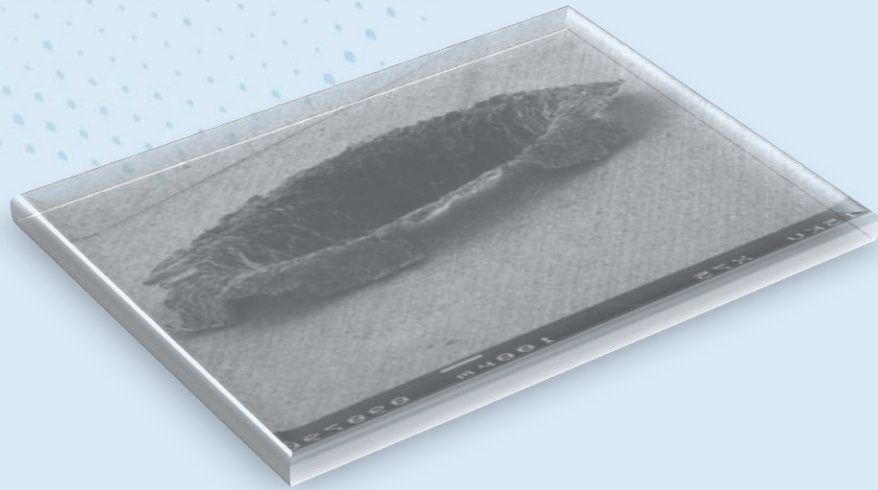
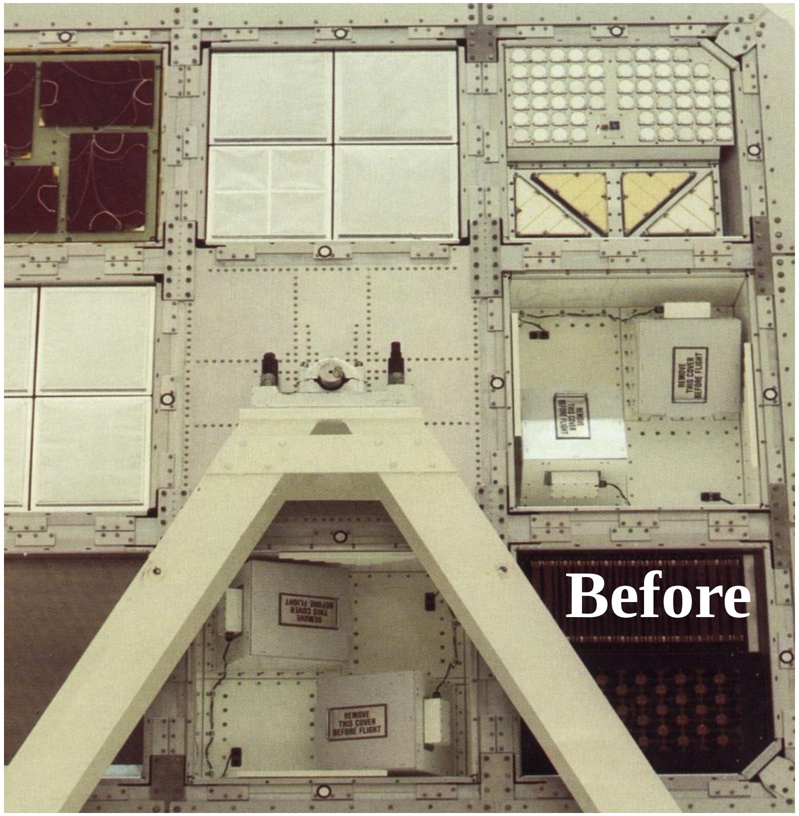
Sun-synchronous orbit **- Ground Station Coverage**

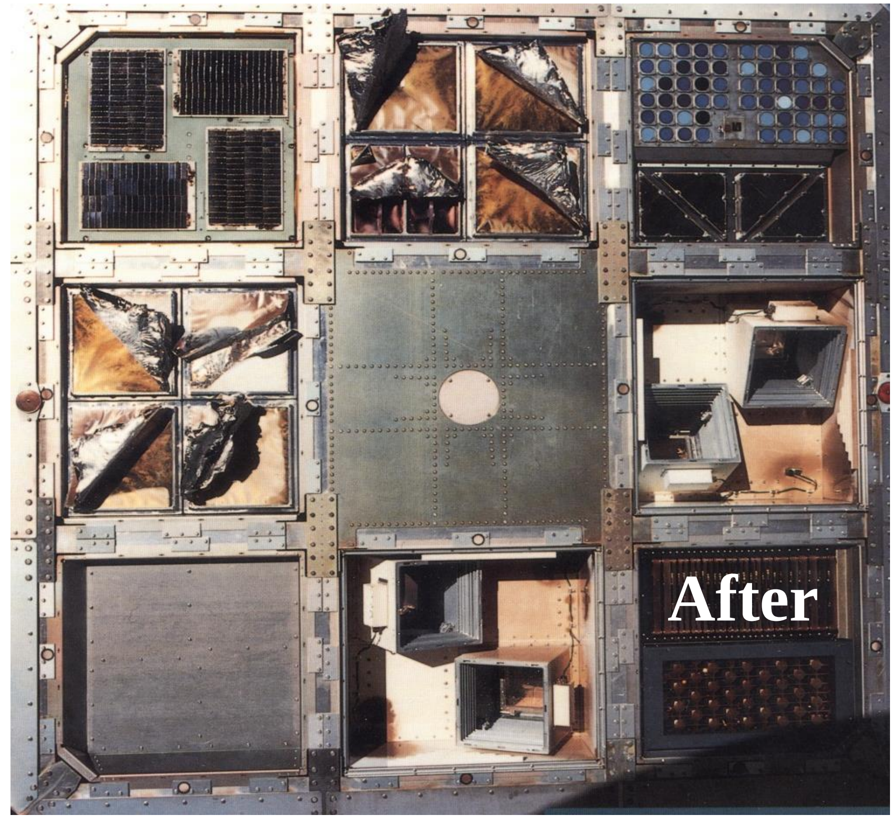


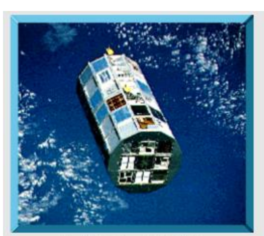
ENVIRONMENTAL CONSTRAINTS



Introduction… we will address details in the solar array chapter…






The LDEF in Low Earth Orbit

LDEF : Long Duration Exposure Facility

NASA space shuttle mission 1984… 1990

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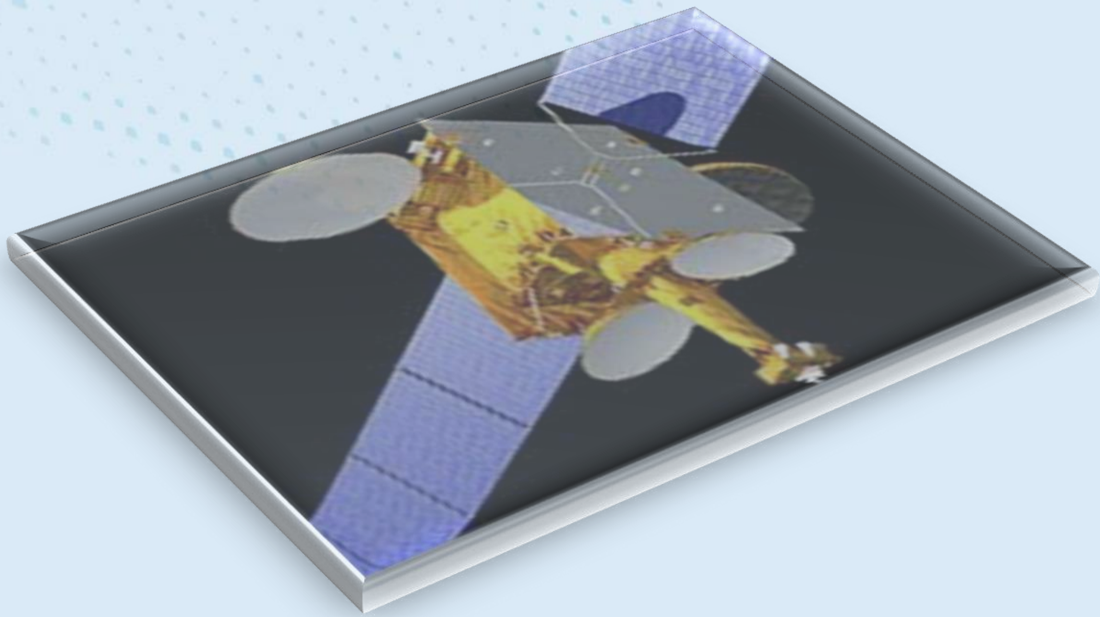
REQUIREMENTS OF ELECTRICAL SYSTEM



Some definitions

Energy

Energy is referred to as the ability to do work. Energy is measured in units called joules, J, or in *watt hours* as shown below.

Watt hours (Wh), are a convenient way of measuring electrical energy. One watt hour is equal to a constant one watt supply of power supplied over one hour (3600 seconds). If a bulb is rated at 40 watts, in one hour it will use 40 Wh, and in 8 hours it will use 320 Wh of energy. Note that one kilowatt hour (1kWh) is equal to 3.6 megajoules.

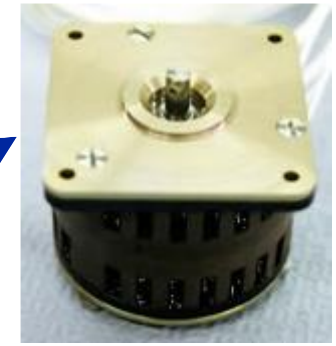
Power

Power is the rate at which energy is supplied (or energy per unit time). Power is measured in *watts*. One watt is equal to one joule supplied per second

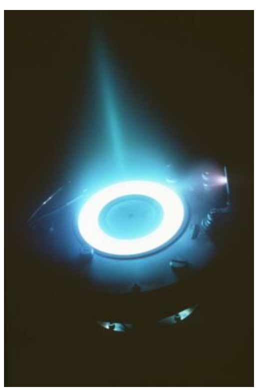
What are the needs for an electrical power system?

Heater → any voltage / 10 to 100 W

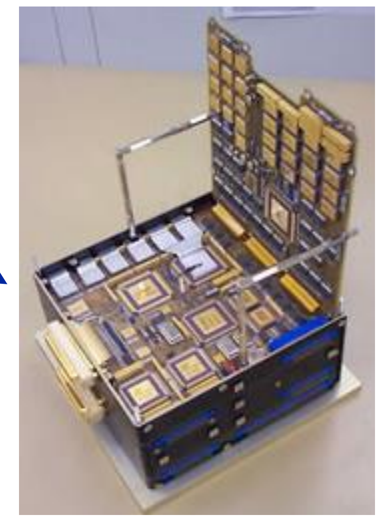
Motor → 28 Vdc



Electric thruster
→ 300V to 2kV
→ 500W to 5kW



Travelling Wave Tube
→ several kV
→ hundreds W



Processor
→ 1V to 3.3 Vdc

What are the needs for an electrical power system?

At the root of power system sizing… the power budget

- **List**, for an operating mode of the space system, **of the individual consumptions of all equipment** in operation

- **Maturity margins** are taken on the typical consumption
- Example:
  - 5% for standard equipment
  - 10% for equipment with minor modification
  - 20% for new one, new development
  - Maturity margins are combined together

- In addition, **system margins are required by the customer** or the project…

What are the need for an electrical power system?

Power budget example

		Basic Consumptions			
	Descriptif	"Stand By"	UHF Relay	Earth Com.	OS search activity
	Durée		10mn x2 x4	2/3 orbit	3 orbits
RF	SDSP RX1	24.0	24.0	24.0	24.0
	SDSP RX2	0.0	0.0	0.0	0.0
	SDSP TX1	0.0	0.0	0.0	0.0
	SDSP TX2	0.0	0.0	0.0	0.0
	TWTA1	8.0	8.0	100.0	8.0
	TWTA2	0.0	0.0	0.0	0.0
	HGA Mechanism	8.0	8.0	8.0	8.0
	USO1	0.0	0.0	0.0	0.0
	USO2	0.0	0.0	0.0	0.0
Data Handling	OBMU	50.0	50.0	44.0	50.0
	DSP + mass memory	13.0	13.0	13.0	13.0
Power	PCDU	18.9	19.5	19.9	19.6
	SA Drive Assembly	9.1	9.1	9.1	9.1
ACS	STR1	12.3	12.3	12.3	12.3
	STR2	0.0	0.0	0.0	0.0
	Gyros+Accéléros 1	32.0	32.0	32.0	32.0
	Gyros+Accéléros 2	0.0	0.0	0.0	0.0
	10 N Thrusters	0.5	0.5	0.0	0.6
	Main Engine	0.0	0.0	0.0	0.0
	Wheel 1	30.0	30.0	45.0	45.0
	Wheel 2	30.0	30.0	45.0	45.0
	Wheel 3	30.0	30.0	45.0	45.0
	Wheel 4	0.0	0.0	0.0	0.0
Harness		10.1	11.9	12.7	12.0
Total Bus		**275.9**	**278.3**	**410.0**	**323.6**
Thermal Control	Orbiter	80.0	80.0	50.0	52.0
	Payloads	0.0	0.0	0.0	0.0
	Propulsion	0.0	0.0	0.0	0.0
Payload	Rendezvous Sample Capture	15.0	15.0	15.0	70.0
	Neige Geodetic Receiver	0.0	13.0	0.0	0.0
	UHF Package	15.0	70.0	15.0	15.0
	Scientific Payload	30.0	30.0	30.0	30.0
	Camera	0.0	0.0	0.0	0.0
Passengers	Netlander1 (Landers + RTU)	0.0	0.0	0.0	0.0
	Netlander2 (Landers + RTU)	0.0	0.0	0.0	0.0
	Netlander3 (Landers + RTU)	0.0	0.0	0.0	0.0
	Netlander4(Landers + RTU)	0.0	0.0	0.0	0.0
	TOTAL	**415.9**	**486.3**	**520.0**	**490.6**

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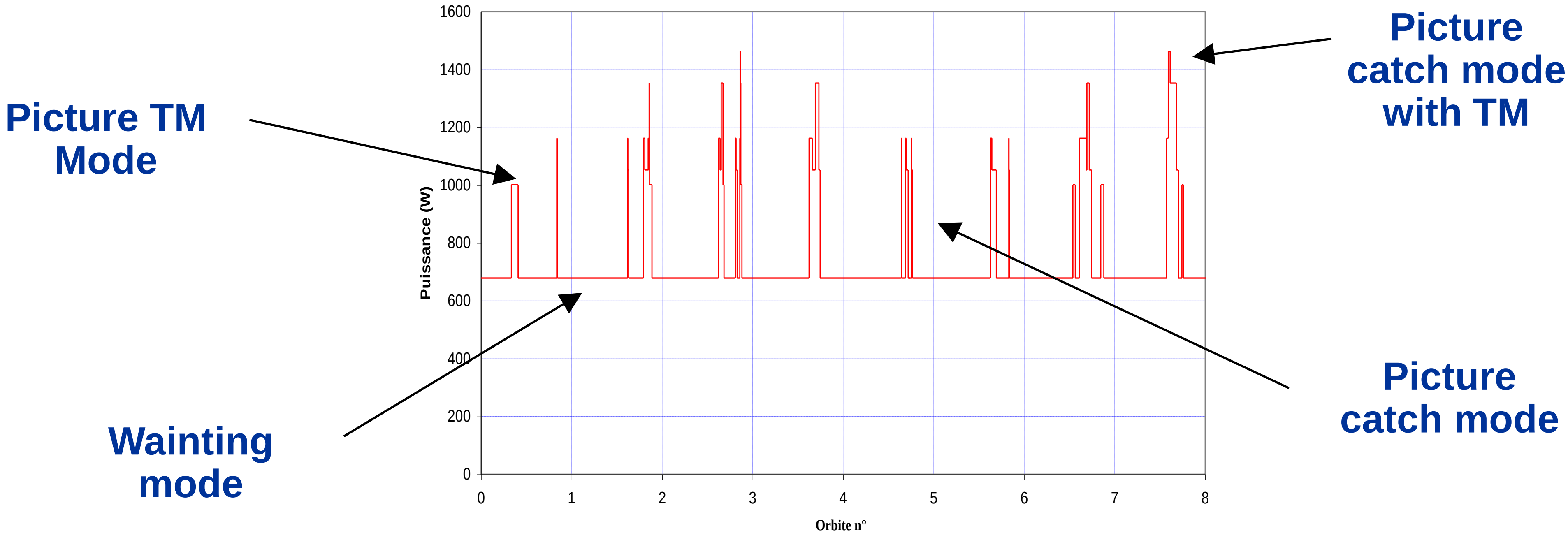
What are the needs for an electrical power system?

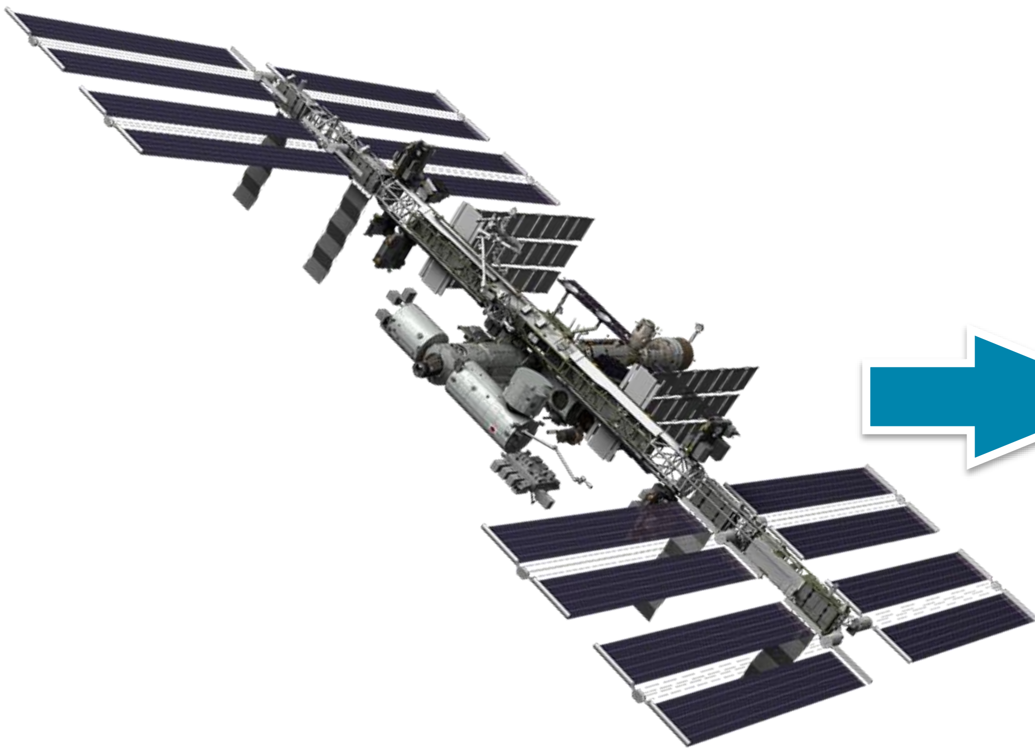
Power profile defines power budget over time

Different consumption represented in a time graphic versus of sequencing of different operating mode



What are the needs for an electrical power system?

- How much power do I need in Space?



International Space Station
84000W

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What are the needs for an electrical power system?

- How much power do I need in Space?

Myriade optical Earth observation
180W

What are the needs for an electrical power system?

- How much power do I need in Space?

7x

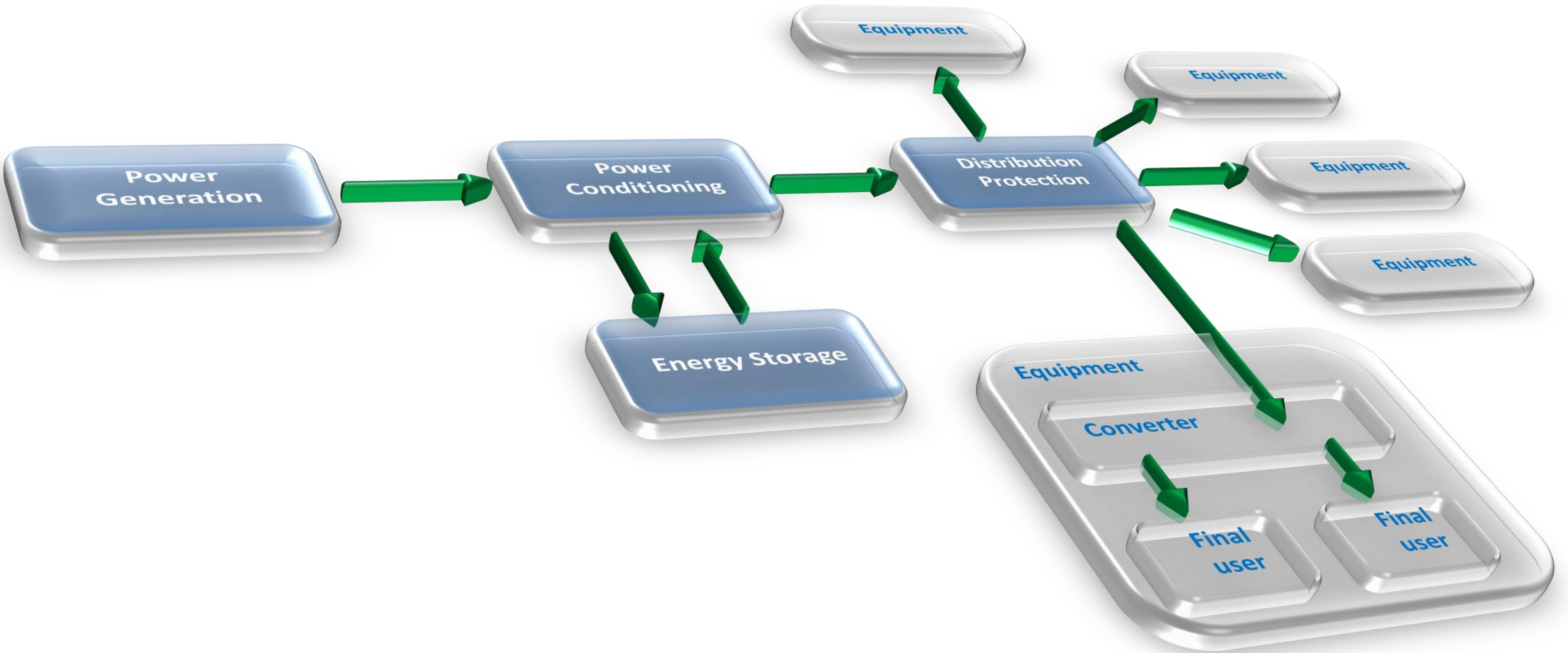
Space Shuttle
21000W

What are the needs for an electrical power system?

- How much power do I need in Space?

ATV (Automated Transfer Vehicle)
4800W

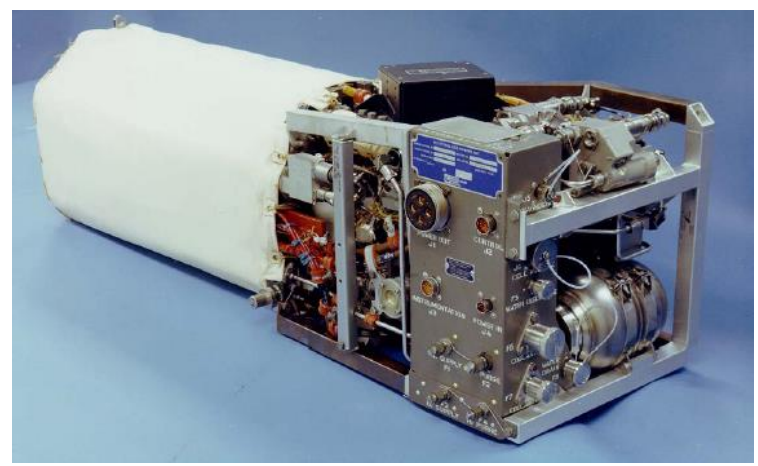
What are the functions of an electrical power system?

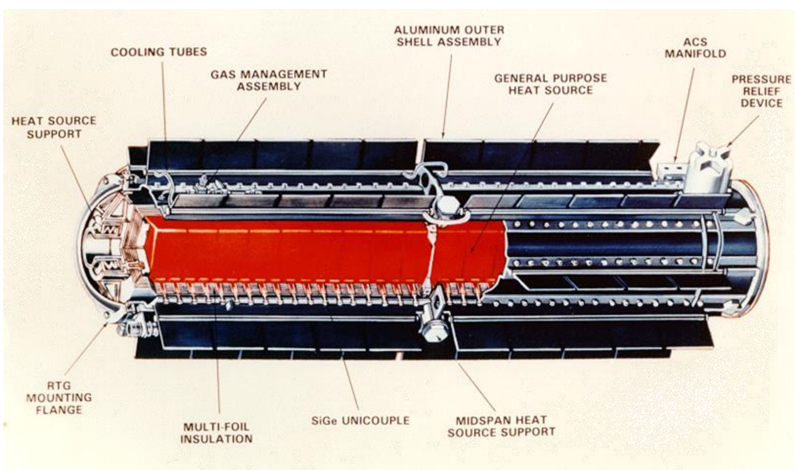


What are the functions of an electrical power system?

Generate power

- **Production of electrical power** from a non-electrical source of energy
- The converted energy can be chemical, nuclear, electromagnetic, thermal,...
- The conversion is ensured by a primary source
  – Primary Cell (LiMnO2, LiSO2…)
  – Fuel Cell (Alkaline, PEM…)
  – RHU / RTG with a thermo-electrical conversion





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What are the functions of an electrical power system?

Store energy

- **Accumulation and restoration of electrical energy**

- The electrical energy is generally converter to and from another form of energy (chemical, mechanical, thermal)

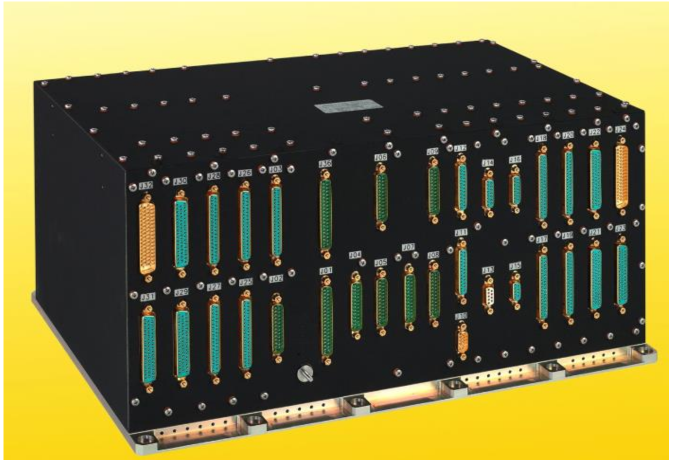
- The storage is ensured by a secondary source

  – Electro-chemical Cell (NiCd, NiH2, Li-Ion…)
  – Supercapacitor
  – Fuel Cell Reversible / Electrolyser
  – Flywheel

Figure 4: 10-cell URFC

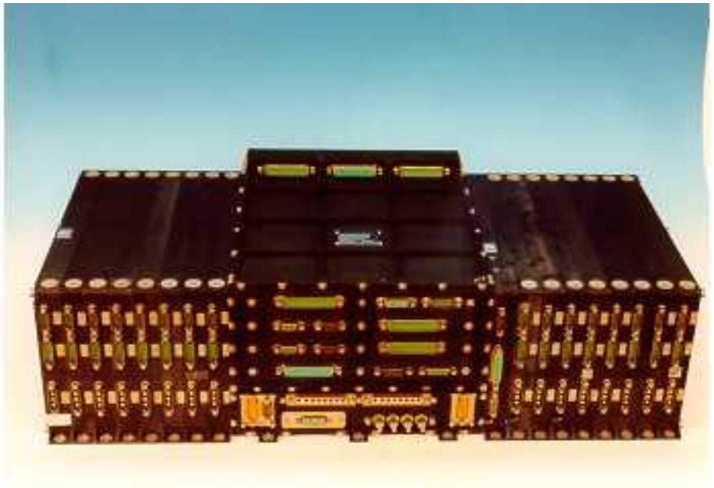
What are the functions of an electrical power system?

Condition power



- All that is necessary for **adapting the primary and / or secondary sources to the needs of the user** equipment...
- ...and ensure the continuity of the electrical power supply
  - PCU (Power Conditioning Unit)
  - PSR (Power Supply Regulator)

Regulate voltage, current, power…



- All that is necessary for **maintaining a voltage or a current or a power at constant level**
- It is generally demanded by the electronic circuits of the end users
  - SAR / ASR (Solar Array Regulator)
  - S3R (Sequential Switching Series/Shunt Regulator)
  - MPPT (Maximum Power Point Tracker)
  - BDR / BCR (Battery Discharge / Charge Regulator)

What are the functions of an electrical power system?

Distribute power

- All that contributes to **carrying the conditioned electric power to the users**
- Generally includes the ON/OFF capability
- Generally excludes harness
  - PDU (Power Distribution Unit)
  - DRU (Distribution and Regulation Unit)

Why the sources are so important?

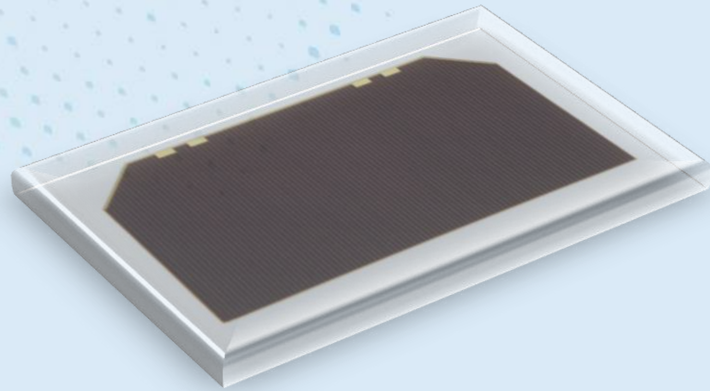
- The **solar generator and the battery together account for 80 to 90 % of the electrical power system mass and cost**

- The power system performance for a given mission is thus heavily dependent on the best possible use of the sources
- The interactions of the power system with the rest of the satellite are such that the a global optimisation must be performed at system level :

  – mass → launch cost, propellant sizing
  – dissipation → radiative area
  – solar generator inertia, stiffness → AOCS disturbance
  – Solar generator field of view → payload interference

- **For the Solar array, the aim is to increase the specific power (W/kg & W/m²)**
- **For the battery, the aim is to increase the specific energy (Wh/kg & Wh/l)**

POWER GENERATION



Power Generation in Space

- How do I get power in Space?

- Any suggestions?

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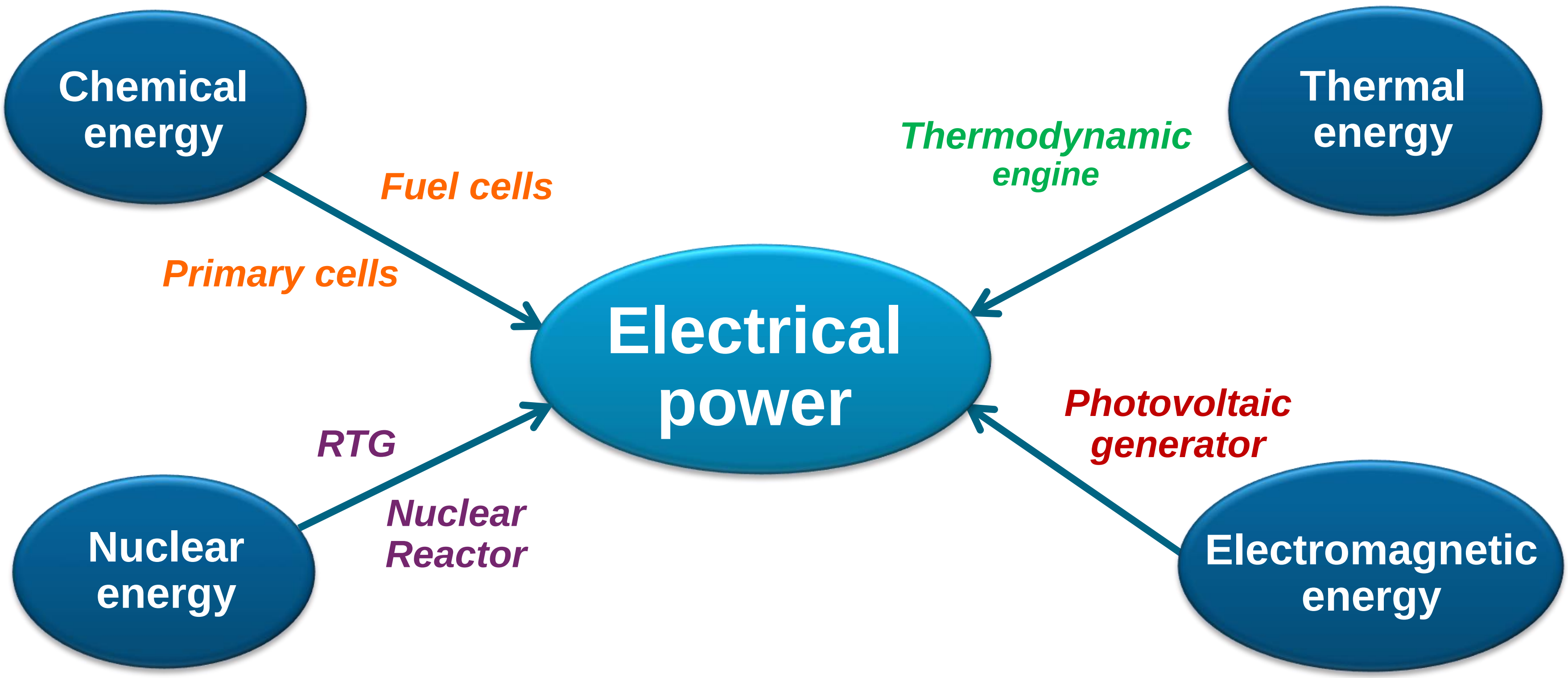
Power generation in space

Two options:

take it with you from Earth… or take it from space environment

… and convert into electrical power.



Power generation in space

- Take it with you from Earth:
  - How?
    - Nuclear energy
    - Chemical energy
    - Thermal energy
  - Advantages:
    - Autonomy
    - High power densities
    - No need for energy storage
  - Drawbacks:
    - No recharge available
    - Limited duration of the mission
    - Higher mass
    - Safety risk

- Take it from the S/C environment:
  - How?
    - Electromagnetic energy from the Sun
    - Thermal energy from the Sun
  - Advantages:
    - Recharge available
    - High energy densities
    - Duration of the mission
    - Lower mass[2]
  - Drawbacks:
    - Dependency on an external source (eclipse)
    - Need for energy storage and more complex power systems.

Power generation in space – primary power sources

Primary batteries

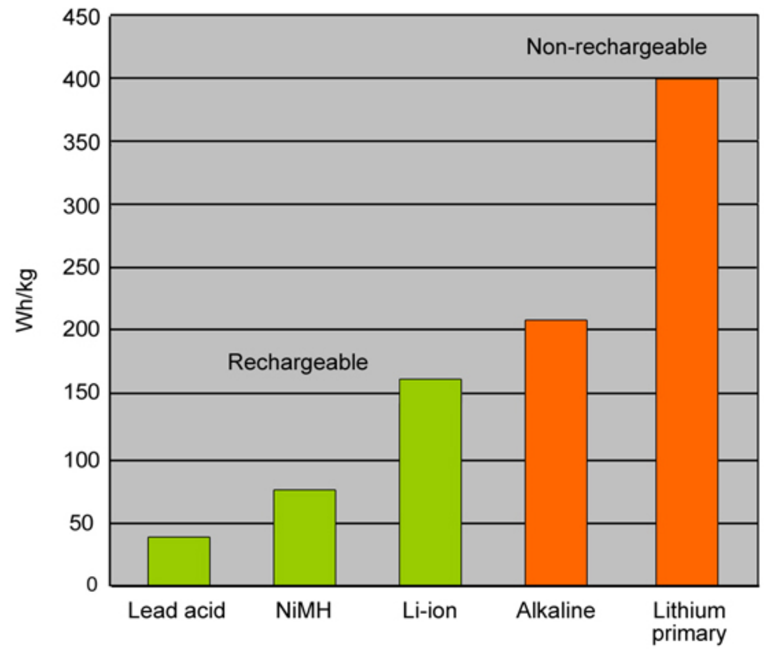
- Primary batteries, also known as **non-rechargeable batteries**.

- **High specific energy**.

- **Long storage times** and Instant readiness: they can be carried to remote locations and **used instantly**, even after long storage.

- Most **common technologies**:
  - **Alkaline** (cost effective and environmental friendly but low load current).
  - **Lithium-metal** batteries perfect for higher capacities.

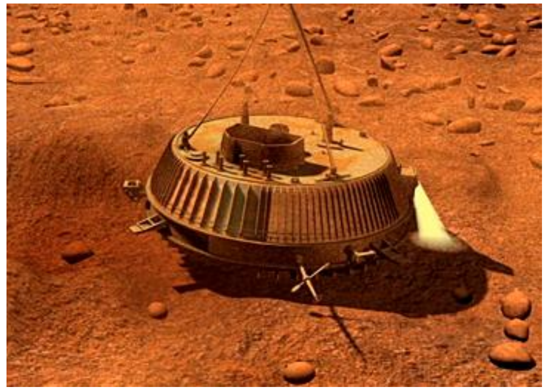
- <u>State of the art :</u> lithium primary battery, specific energy >> 250 Wh/kg.



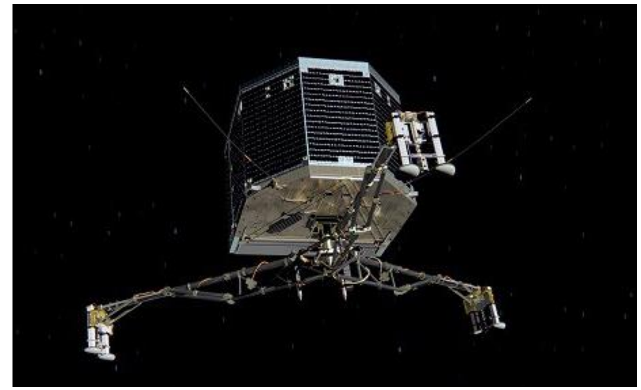
Power generation in space – primary power sources

Primary batteries – Typical applications

- **Launchers**
- **Planetary probes**
- **Orbital transfer vehicle**



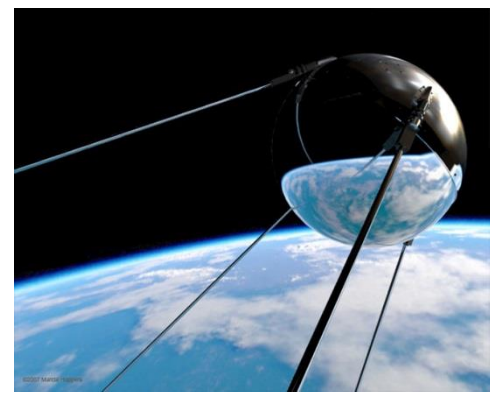
Huygens – $LiSO_2$ (1600 Wh -250W 3 hours)



Philae – SAFT LSH20 (1000 Wh 3kg – 60 hours)

Ariane 5 - AgZn

ATV – $LiMnO_2$ (2 for separation and 1 for Emergency procedures)



Sputnik 1– AgZn (51kg – 22 days)

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Power generation in space – primary power sources

Fuel cells

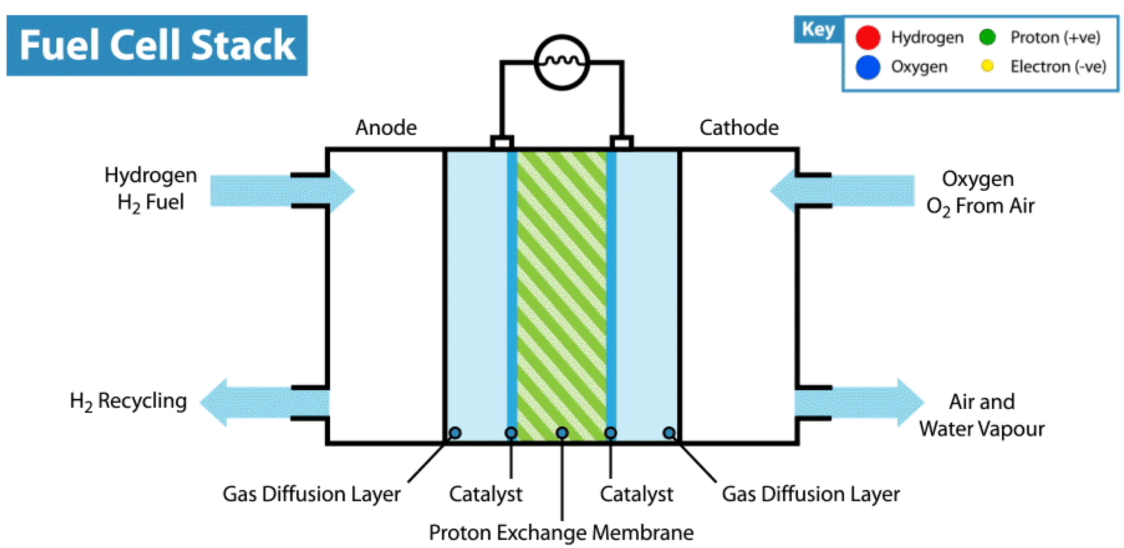
- A **fuel cell produces electricity, water and heat** directly from hydrogen (**H_2**) and oxygen (**O_2**) without combustion.

- Fuel cells are **like batteries** in that they are **electrochemical devices**, but **unlike batteries** do **not need recharging** and will **continue to operate as long as they are provided with fuel** (hydrogen).

- The **autonomy is limited** by the capacity to bring sufficient combustibles (H_2 and O_2 tanks)

- Useful for **large power / low energy** or **Large energy / low power** applications

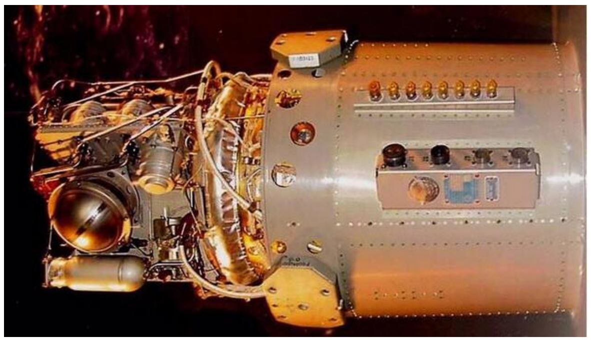
- **A fuel cell can be more than twice as efficient as an internal combustion engine**. A conventional engine burns fuel to create heat and in turn converts heat into mechanical energy and finally electricity.



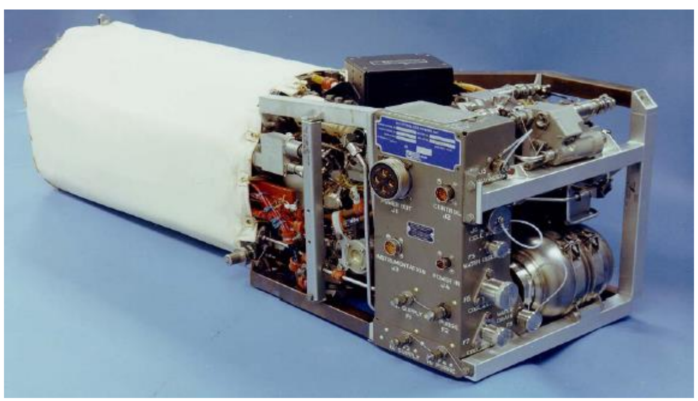
Power generation in space – primary power sources

Fuel cells – Typical applications

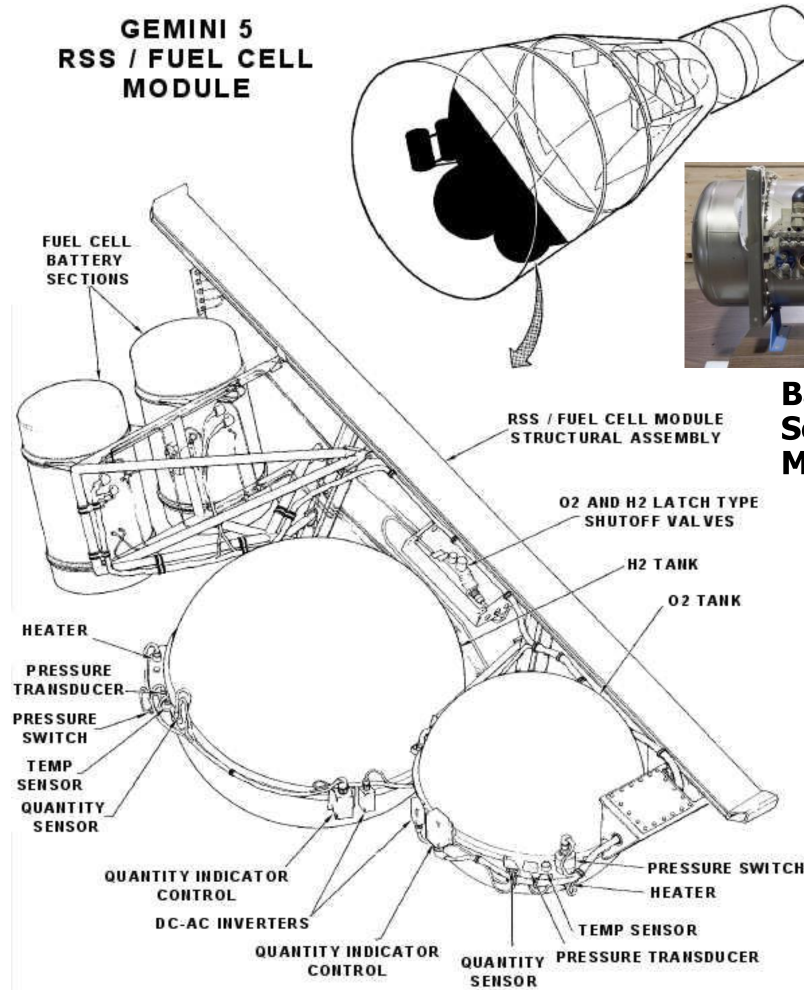
- **Human flight for short duration about a week**

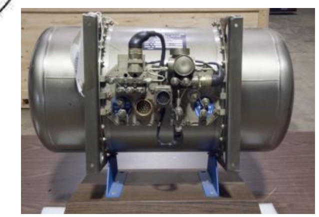


Apollo SM102 Fuel Cell.
Power output 563 to 1420 W. Max 2.3kW



Space shuttle ; 116kg, 115 x 38 x 36 cm
Max 7kW





Battery Section
Max 1kW

Gemini 5 doubled, thanks to fuel cells, the U.S space-flight record to eight days, the length of time it would take to fly to the Moon, land and return.

Power generation in space – primary power sources

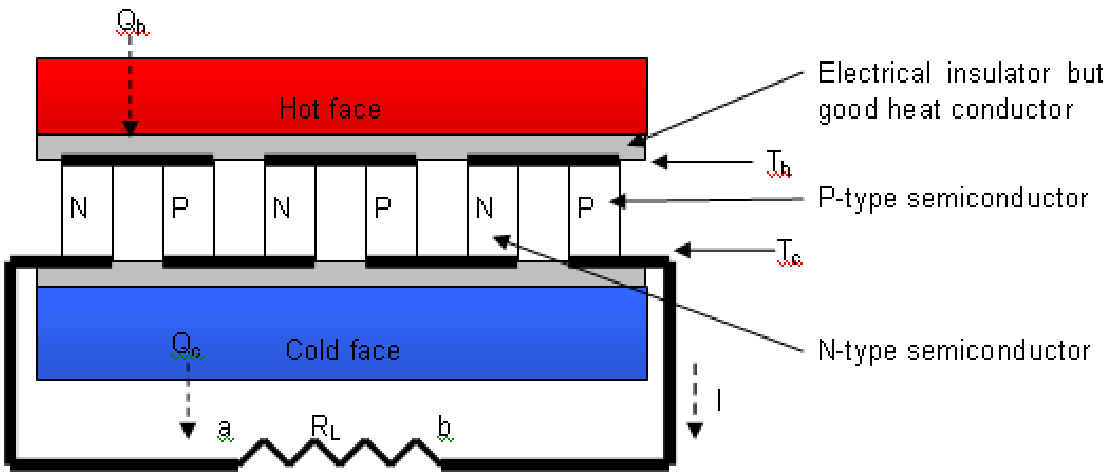
Radioisotope thermoelectric generator (RTG)

- An electrical generator (with no moving parts) that **uses an array of thermocouples to convert the heat released by the decay of a suitable radioactive material (^{238}Pu in oxyde)** into electricity by the **Seebeck effect**.

- Nuclear energy is the **only one capable to provide power for very long period and far from the Sun.**

- **Most desirable power source** for **unmaintained situations** that need a **few hundred watts (or less)** of power for **durations too long for fuel cells, batteries, or generators** to provide economically, and **in places where solar cells are not practical**

- Low efficiency (< 6%) → **Important heat generation** → Need for **radiators**.

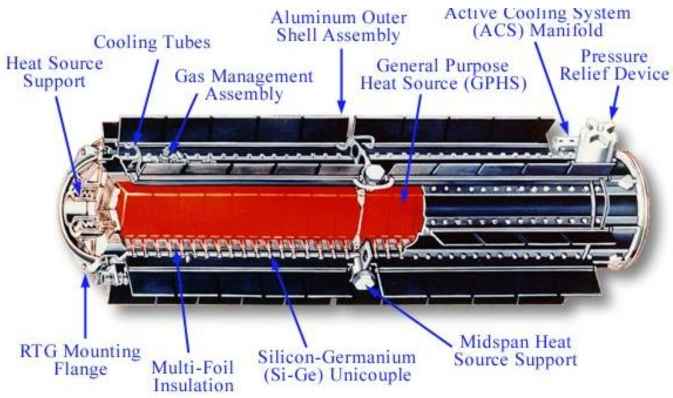


Seebeck effect is the conversion of heat directly into electricity at the junction of different types of wire composed of materials of different Seebeck coefficient (p-doped and n-doped semiconductors)

Power generation in space – primary power sources

Radioisotope thermoelectric generator (RTG) – Typical applications

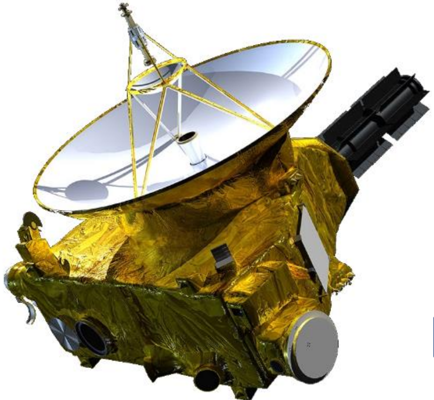
- **Interplanetary exploration beyond Jupiter**
- **Lunar or Martian rovers**



GPHS RTG - Galileo, Cassini, Ulysses & New Horizons
292W – 19 years (still on-going)

SNAP-19 RTG used on Viking and Pioneer
42W – 30 years for Pioneer 10
(Communication lost)

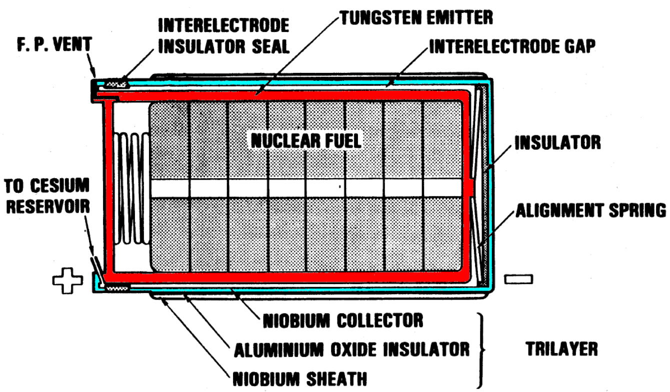
Multi-mission MMRTG – MSL, Curiosity
110W – Based on SNAP-19

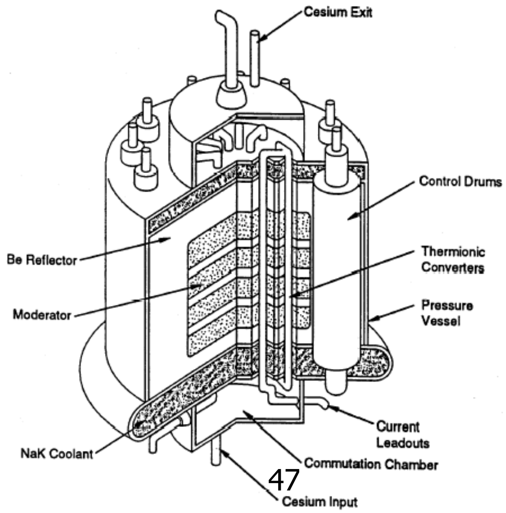


Power generation in space – primary power sources

Nuclear reactor

- Same principle than civil reactor: **Heat from nuclear fission** is passed to a working fluid (water or gas), which runs through turbines
- **But electricity is supplied by thermo-ionic conversion:** a hot electrode which thermionically emits electrons over a potential energy barrier to a cooler electrode, producing a useful electric power output (5 to 10kWe from 115 to 150kWth).
- **Typical application :** Soviet satellites in the years 1970-90 (**COSMOS**), Russian exclusivity: **TOPAZ reactor (10kW).**





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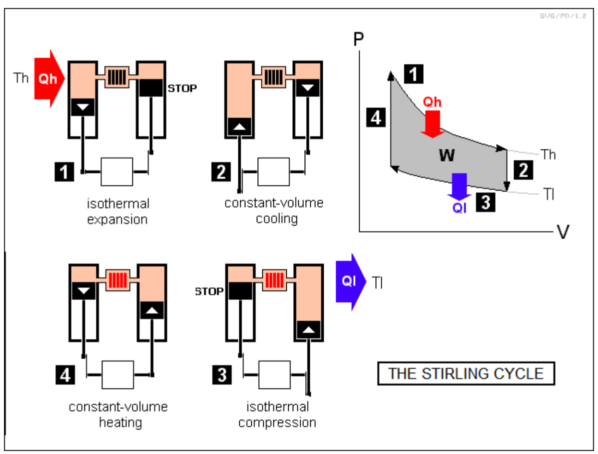
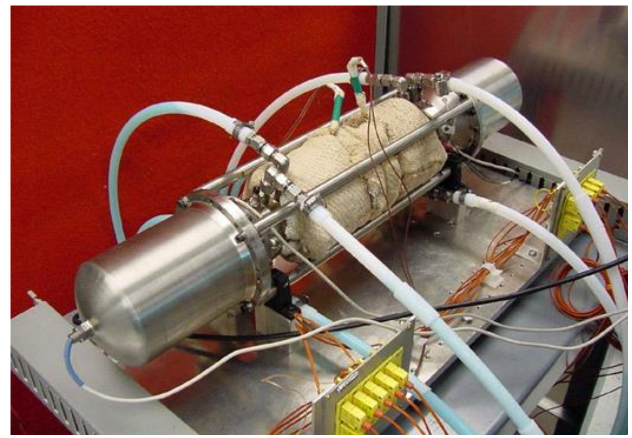
Power generation in space – primary power sources

Stirling thermodynamic machines (also thermo-acoustic engine)

- **Need to have a hot source** (example: **nuclear reactor** or Radioisotope Heater Unit (RHU) or **solar concentrator**…)
- And **a cold source** (**radiator** to space)
- A Stirling engine is using these sources **to move a piston and AC generator**
- **High efficiency** compared to thermoelectric conversion (≈ **30%)**
- But **complex, heavy and moving parts**



$$\eta = 1 - \frac{Tcold}{Thot}$$

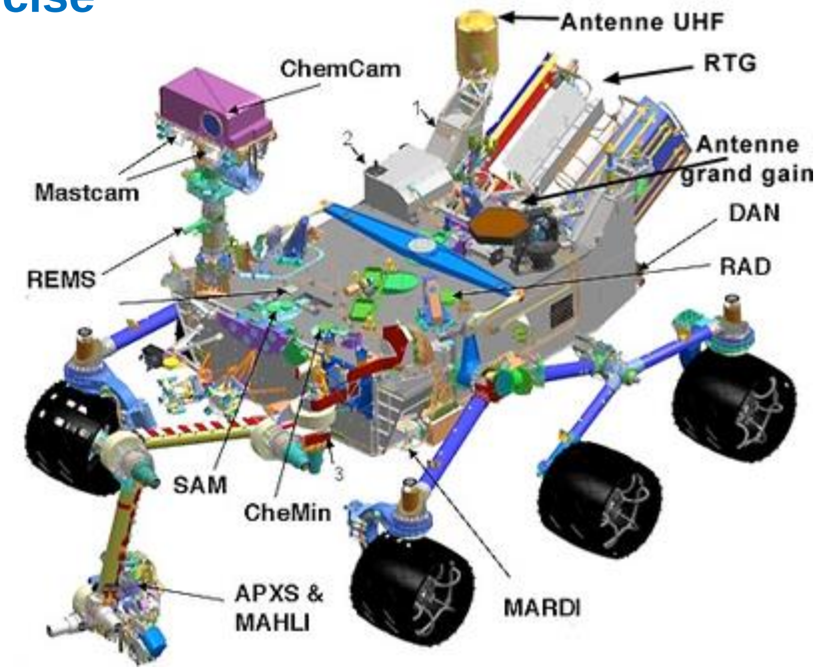


Lockheed Martin Stirling Radioisotope Generator

Hot end temperature:	**650°**
Cold end temperature:	**120°C**
Output:	**112W DC (BOL)**
Converter efficiency:	**23% (system)**
Mass:	**27kg**
Dissipation:	**375W**
Radiator area:	**0.32m²**

Power generation in space – primary power sources

Radioisotope thermoelectric generator (RTG) - Exercise



Hypotheses:

- **A rover** requires:
  - 150W electrical power during 12h
  - 50W electrical power during 12h
- ^{238}**PuO2** generates heat **390W/kg**
- RTG conversion efficiency: **6%**
- Energy storage performance: **200Wh/kg**

Questions:

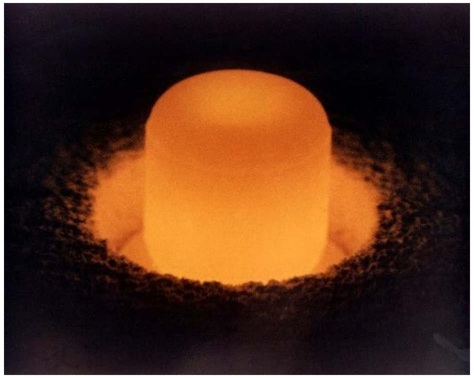
- **What are the two possible power system architectures?**
- **What is the optimal total mass of Plutonium oxyde required for the rover?**

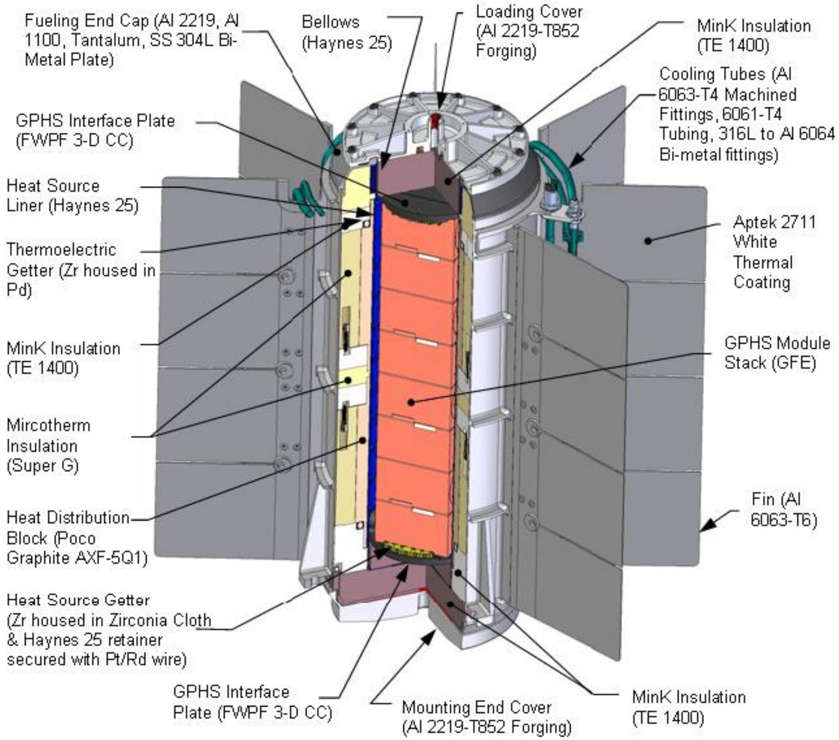
Power generation in space – primary power sources

Radioisotope thermoelectric generator (RTG) - Solution

- **Option 1: size the RTG according to maximal power**
  - 150W maximal electrical power
  - 150W / 6% = 2500W thermal power
  - 2500W / 390W/kg = 6,4kg of PuO2

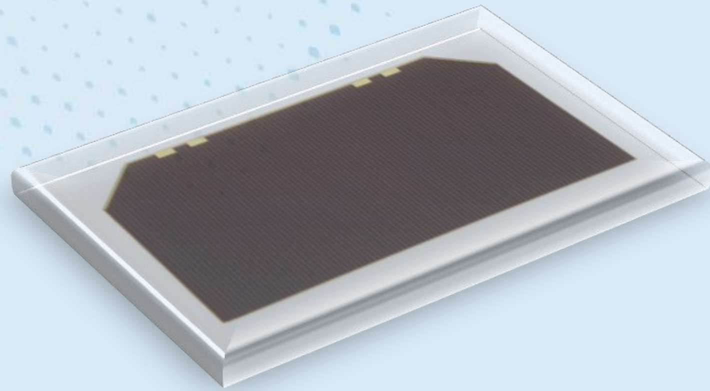
- **Option 2: size the RTG according to average power**
- **Use energy storage device**
  - 100W maximal electrical power → 4,3kg of PuO2
  - Required stored energy = 50W x 12h = 600Wh
  - 600Wh / 200Wh/kg → 3kg of batteries





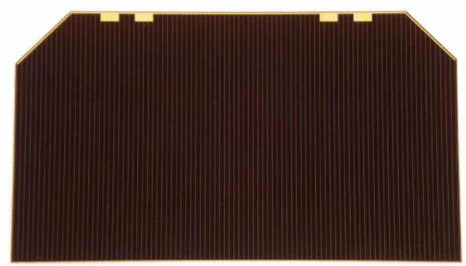
Coffee Break

PHOTOVOLTAIC POWER GENERATION



Introduction to photovoltaics

- Photovoltaics is the **process of converting sunlight directly into electricity** using solar cells
- The **first practical photovoltaic** devices demonstrated in the **1950s** at Bell Laboratories.
- **Vanguard 1 (1958)** first satellite to be solar powered (US), fourth satellite after Sputnik. **Six solar cells.**
- Research and development of photovoltaics received its first **major boost from the space industry in the 1960s**

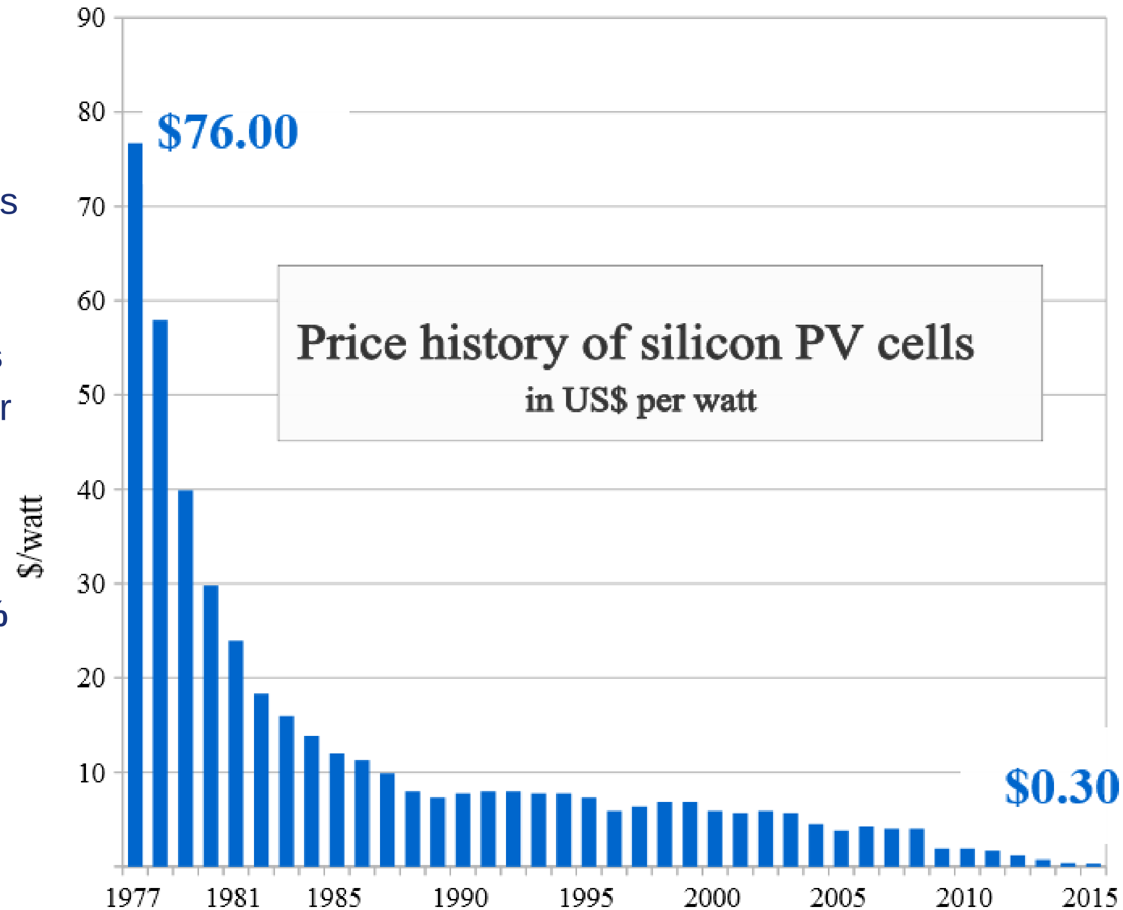


Typical size :

Thickness: 50 to 350 µm
Length: 20 to 80 mm
Width: 20 to 60 mm

Introduction to photovoltaics

- Space solar cells were several thousand times more expensive than they are today
- In the 1980s research into **silicon solar cells** paid off and solar cells began to increase their efficiency. In 1985 silicon solar cells achieved the milestone of **20% efficiency**
- **Current maximum efficiency record: 44.7%** (Fraunhofer ISE and Soitec)
- Price comparison:
  - Space: 200 $/Watt
  - Terrestrial: <1 $/Watt



Source: Bloomberg New Energy Finance & pv.energytrend.com

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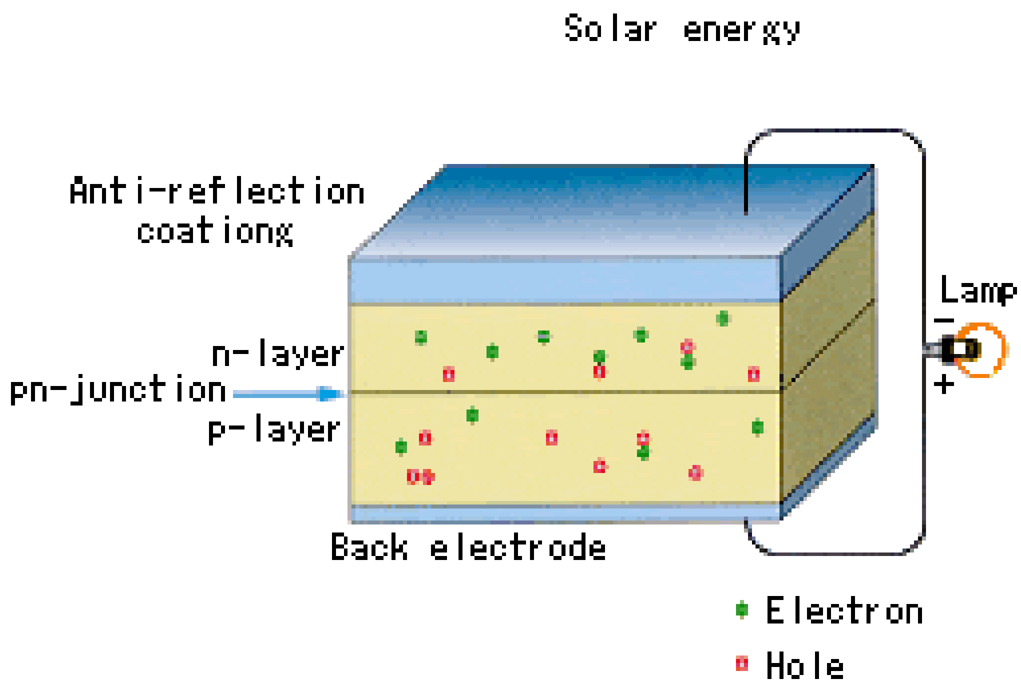
Introduction to photovoltaics

Video

Working principle

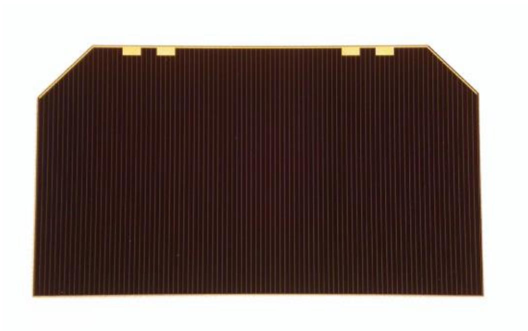


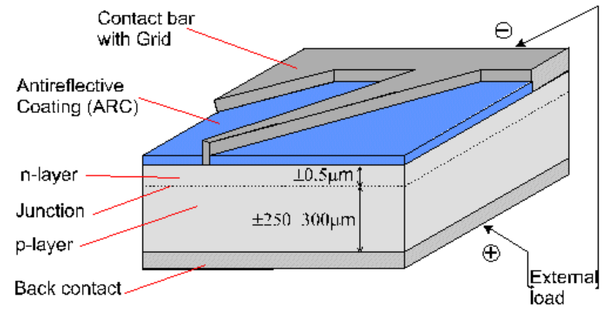
SOLAR CELL

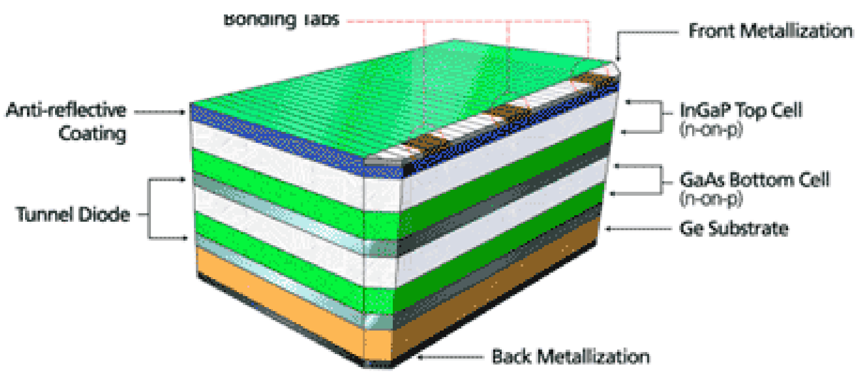
Solar cell description

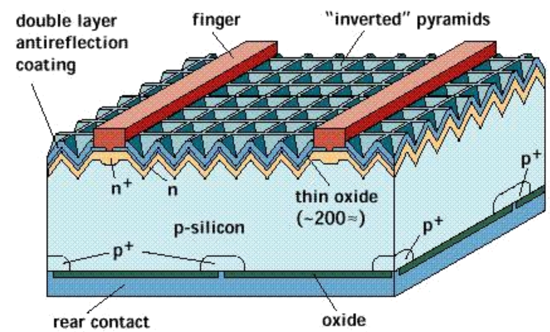
Typical sizes :

Thickness: 50 to 350 µm
Length: 20 to 50 mm
Width: 20 to 60 mm



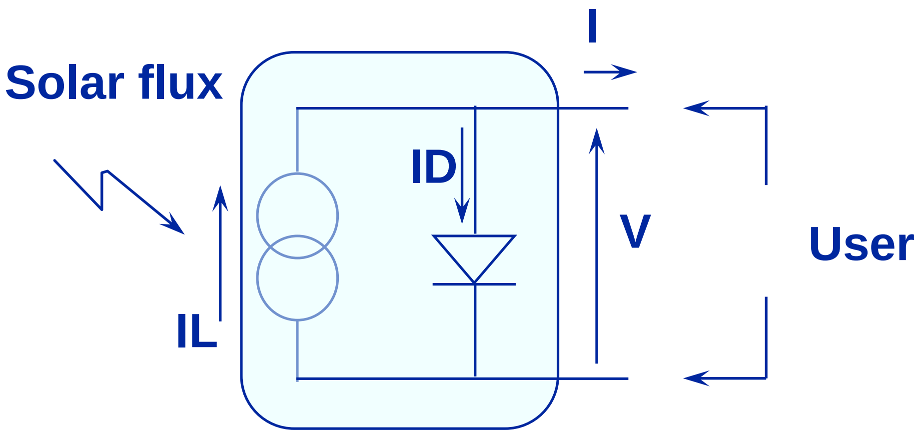


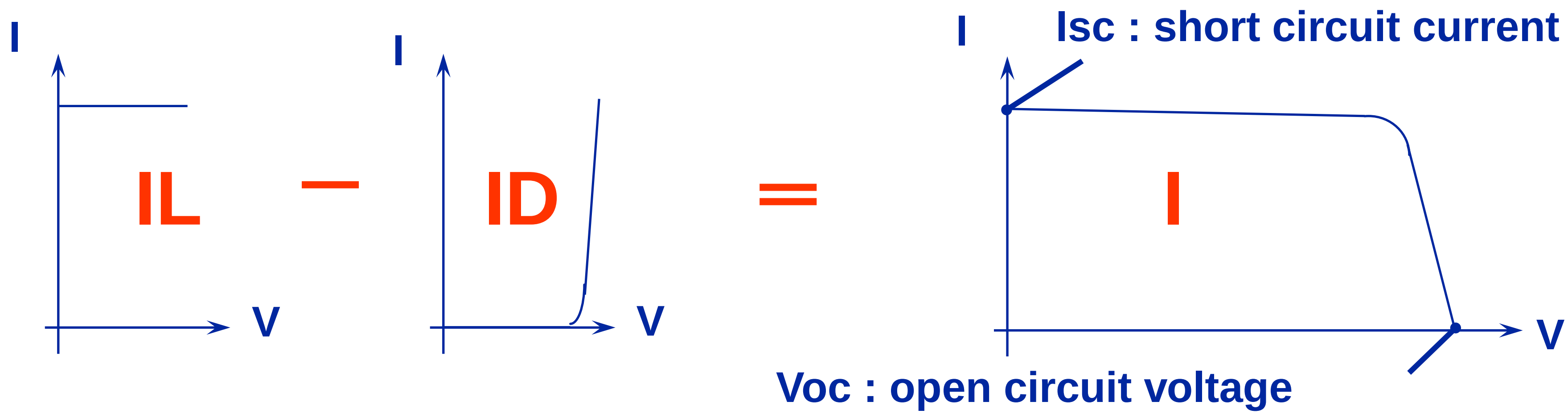




SOLAR CELL

Equivalent static model





SOLAR CELL

Pmax : maximal power

Vmp : Voltage for Pmax

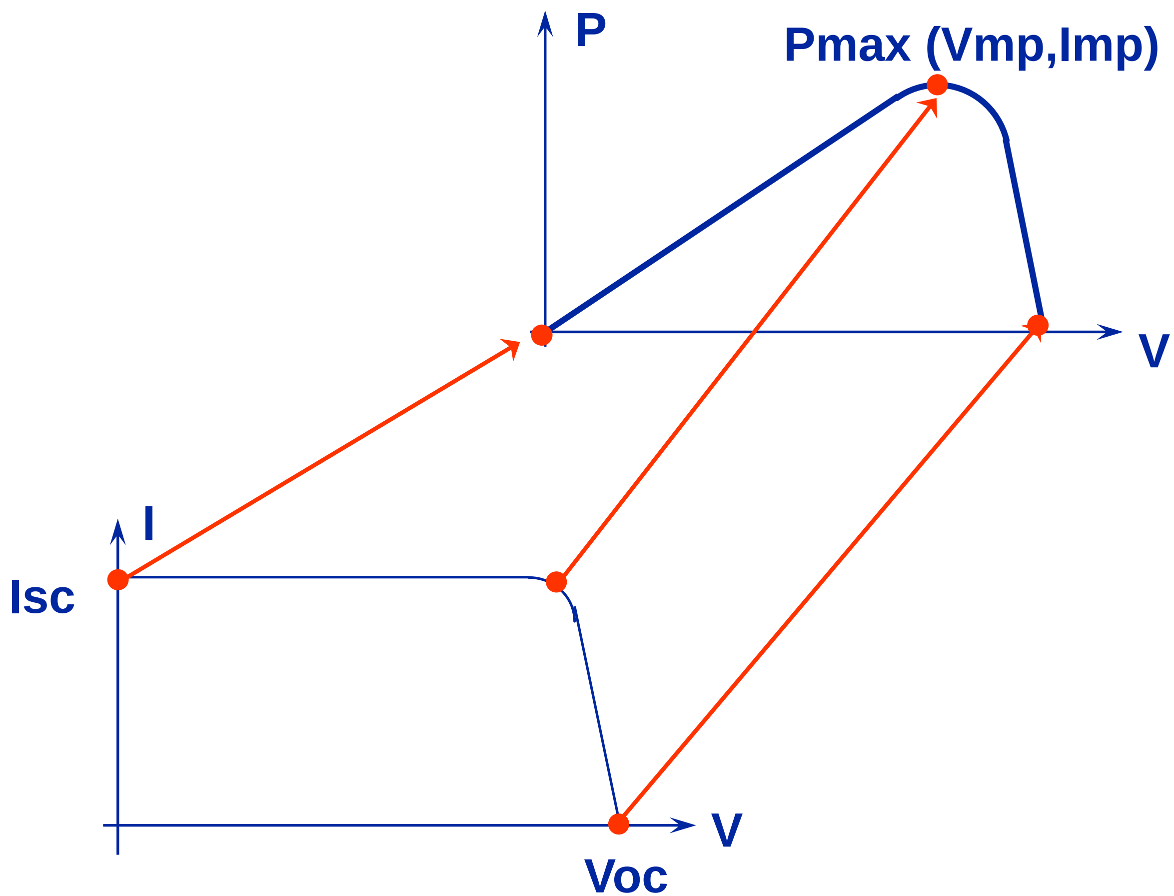
Imp : Current for Pmax

Equivalent static model

$$\boxed{I(V) = Icc - Io\, e^{\alpha V}}$$

$$\alpha = \frac{Log\left(1-\frac{Imp}{Icc}\right)}{Vmp - Vco}$$

$$Io = Icc\, e^{-\alpha Vco}$$



SOLAR CELL

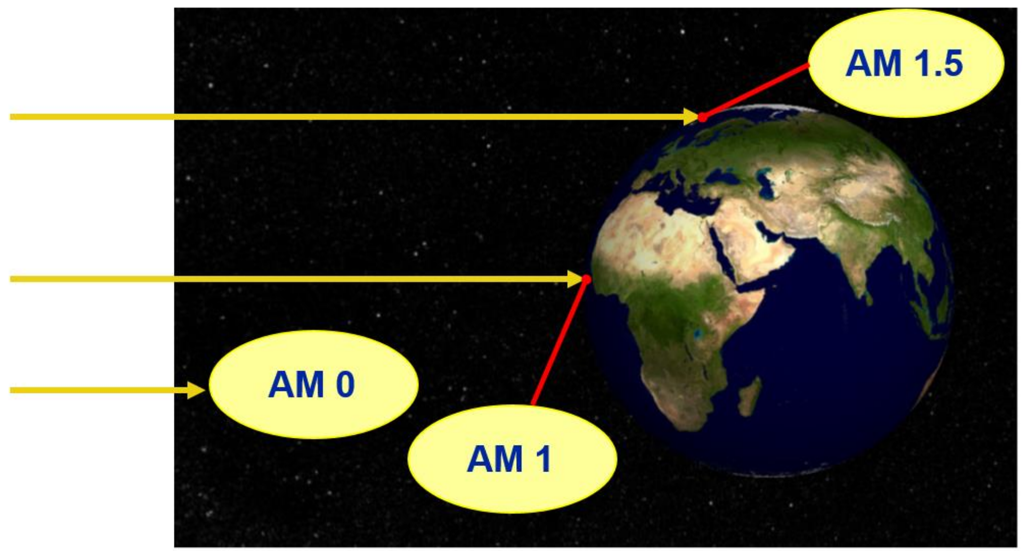
Sun Intensity

❑ Solar Constant

- It is the intensity of the solar flux outside the atmosphere at a distance from the Sun equal to 1 astronomical unit
  (1372 Watts / m²).

❑ Air Mass

- It is the number of “atmospheres” interposed between the sun and the surface where the flux is measured:
  - AM0 = Outside the atmosphere,
  - AM1: Horizontal surface at the equator at noon on 21 March,
  - AM 1.5 = A horizontal surface at Bangkok on 21 June 3:30 p.m.



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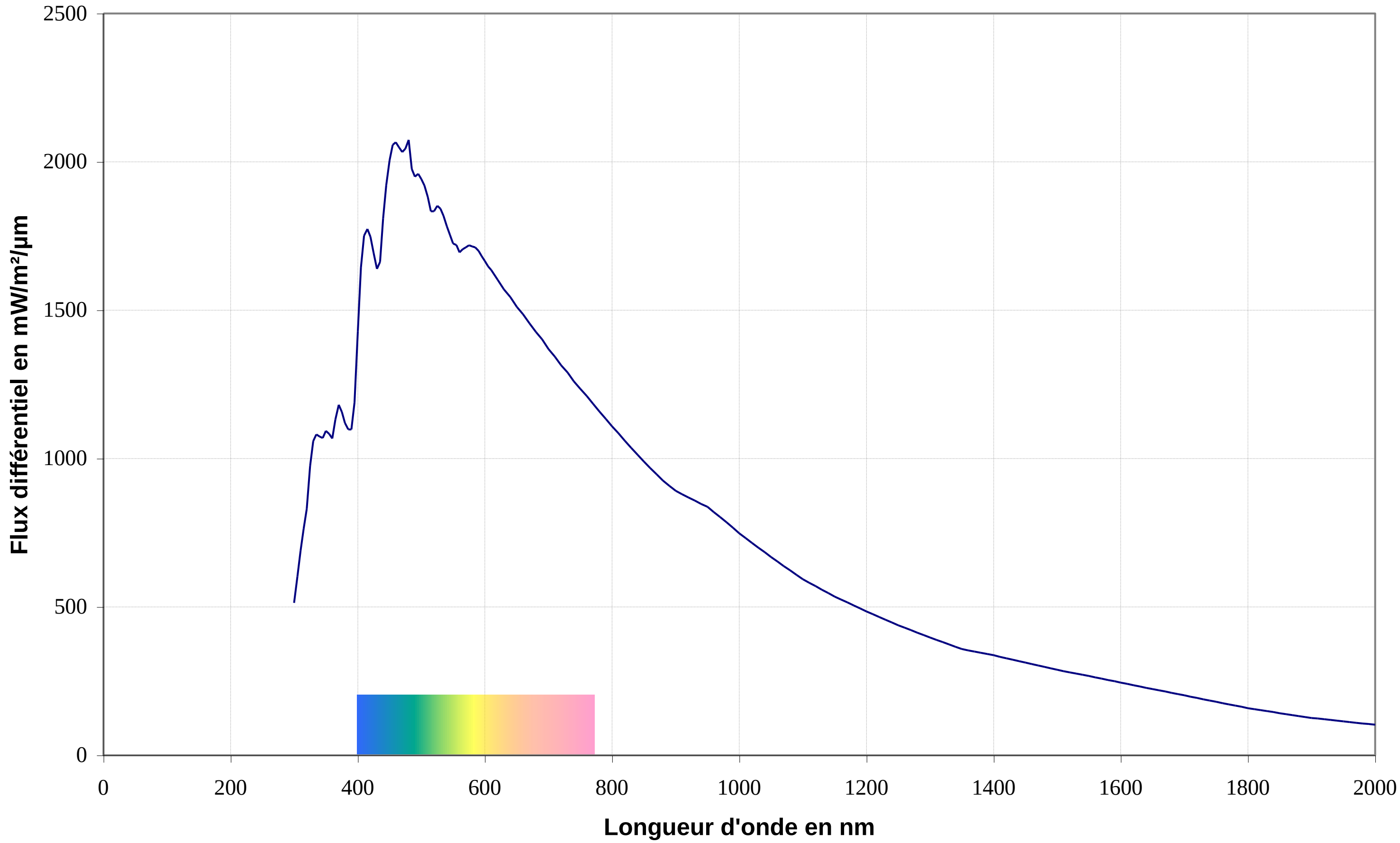
SOLAR CELL

AM0 solar spectrum

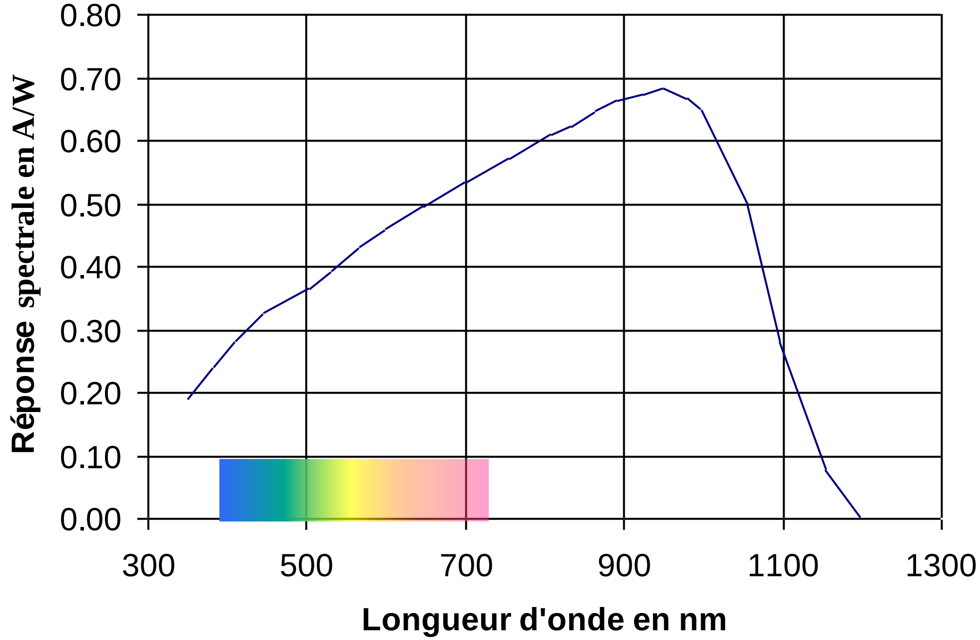


SOLAR CELL

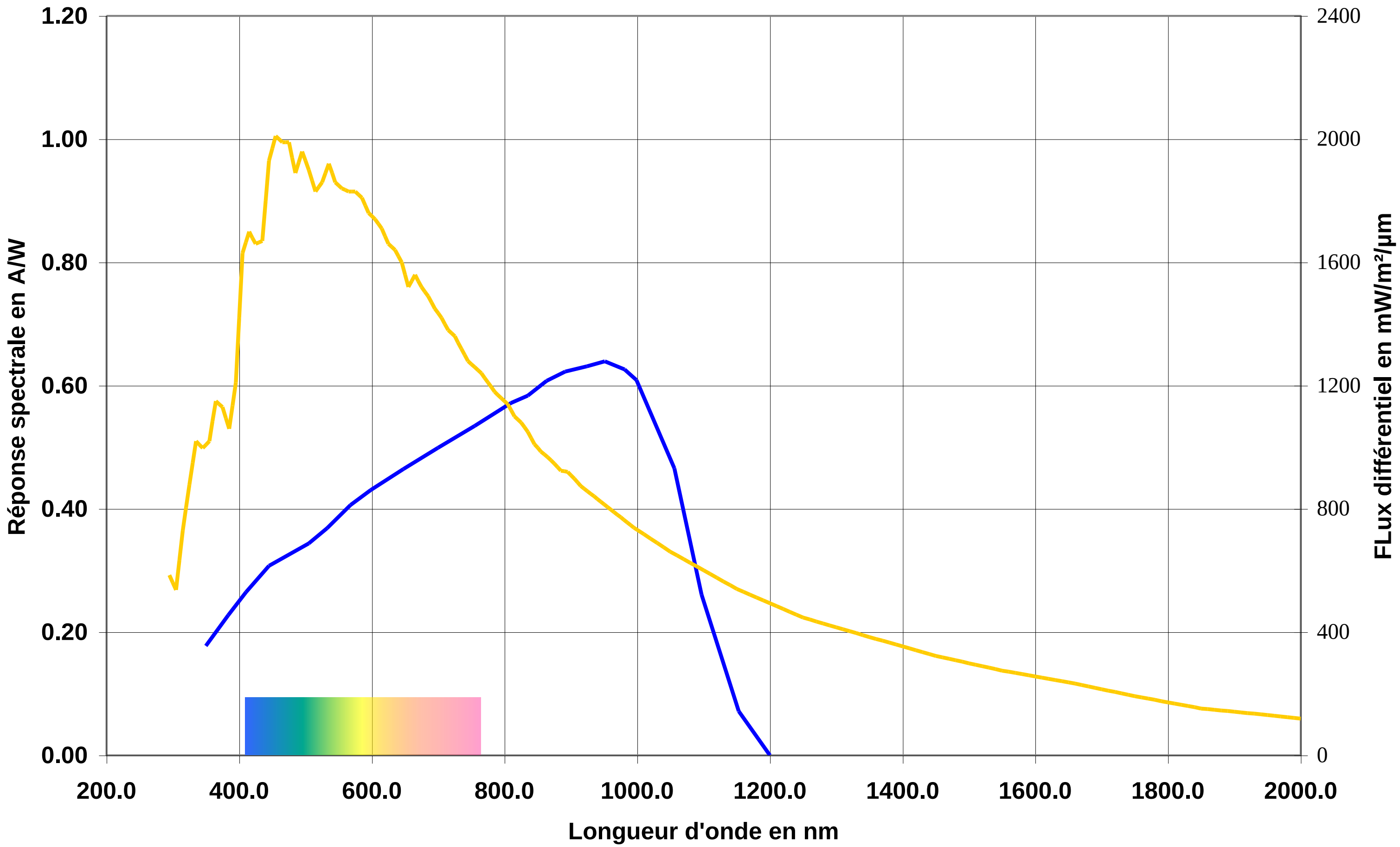
Spectral response

- the way the conversion efficiency of a solar cell varies with the light wavelength depends on its constituting material and fabrication process

- the corresponding curve is the solar cell spectral response (A per W for each wavelength)



SOLAR CELL



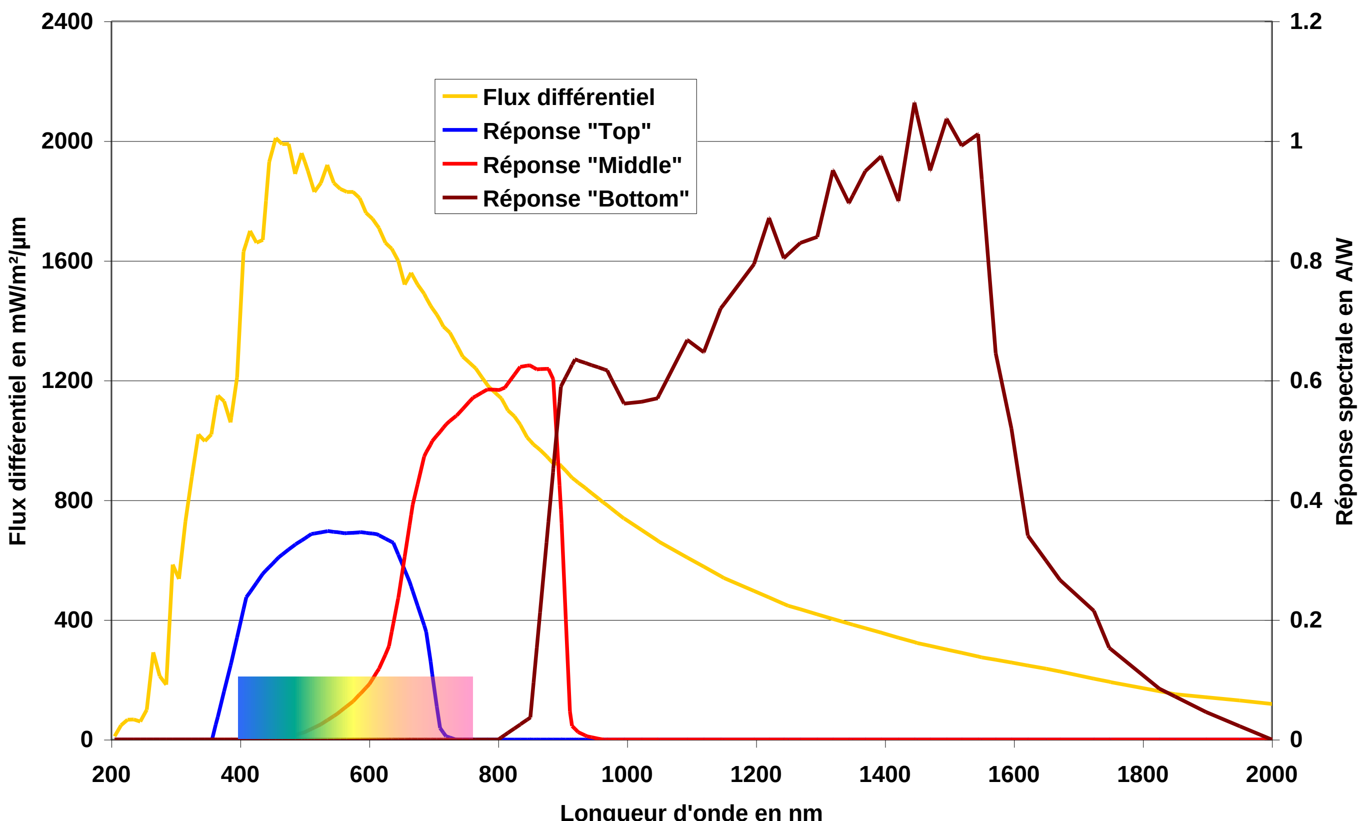
Use of the sun energy in this domain is poor

This part of the Sun spectrum is not used at all by the cell

SOLAR CELL

Multi junction solar cells

Several junctions are optimized for different parts of the Sun spectrum. They are monolithically connected in series



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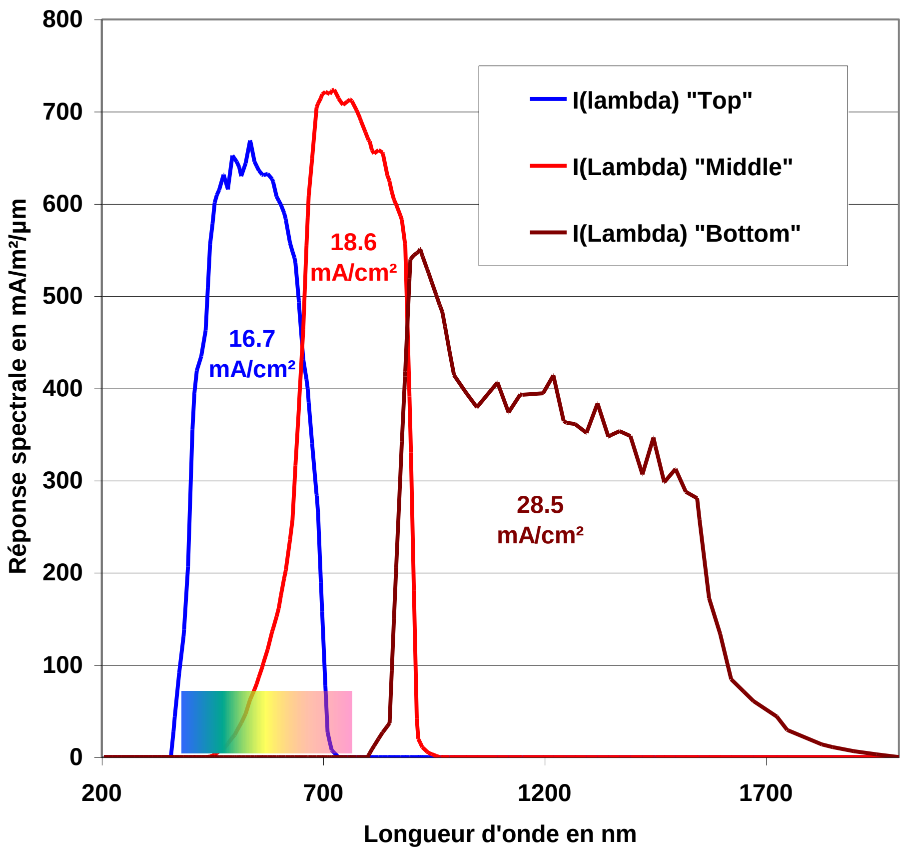
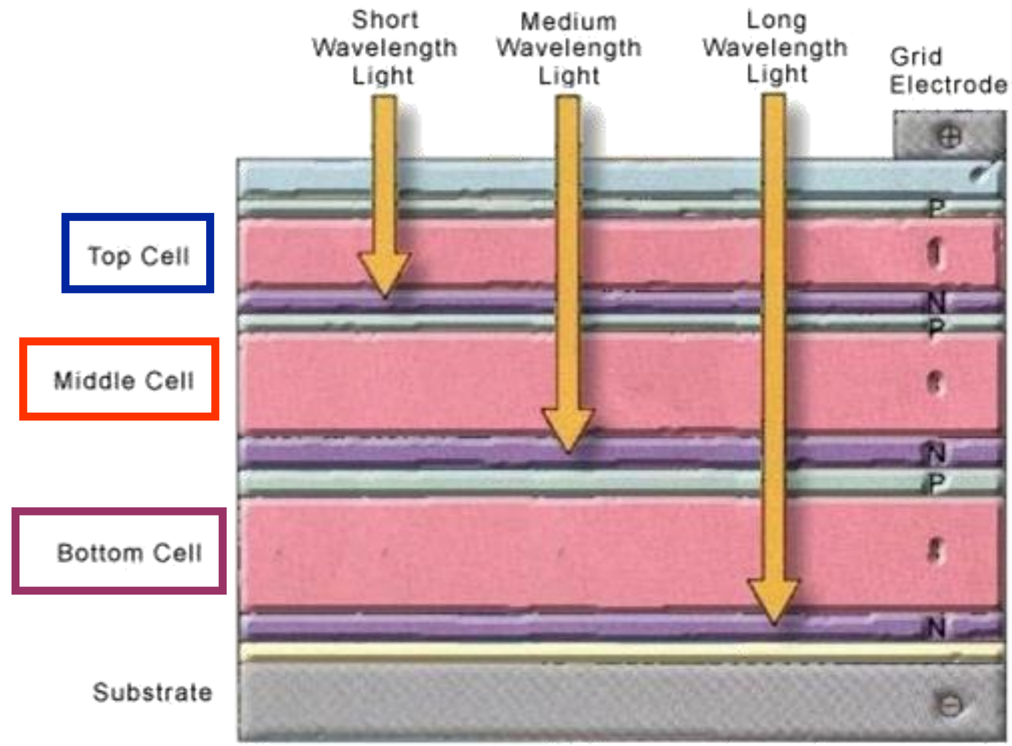
SOLAR CELL

Multi junction solar cells





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SOLAR CELL

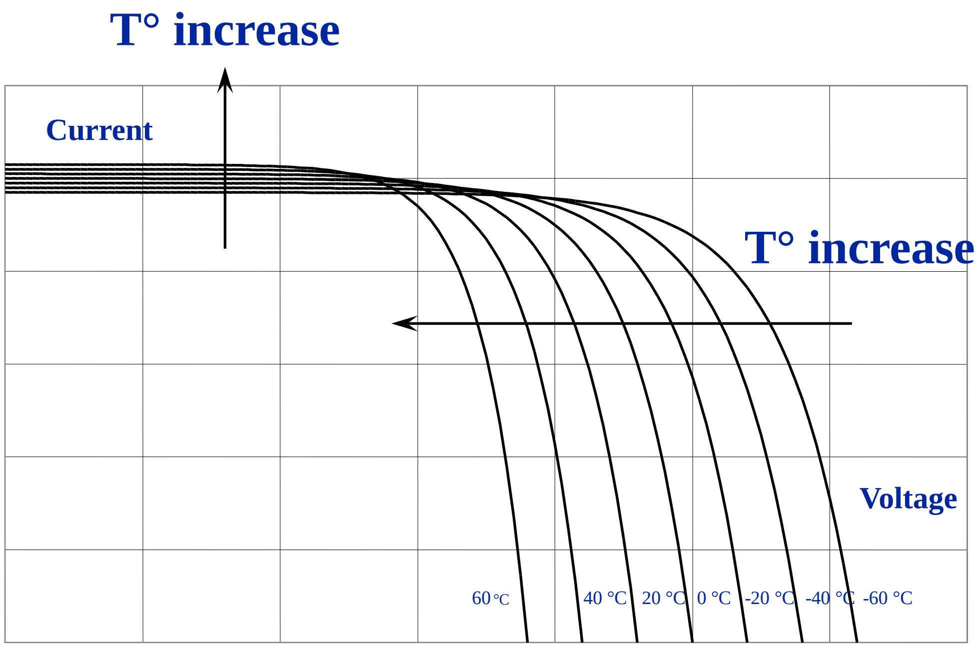
Temperature influence

- LEO orbits **-80°C … +80°C**

- GEO orbits **-185°C … +50°C**
- EOR down to **-195°C**

- Mercury **>200°C** with high solar array tilt of 80°

- Jupiter **-220°C** for the longest eclipse

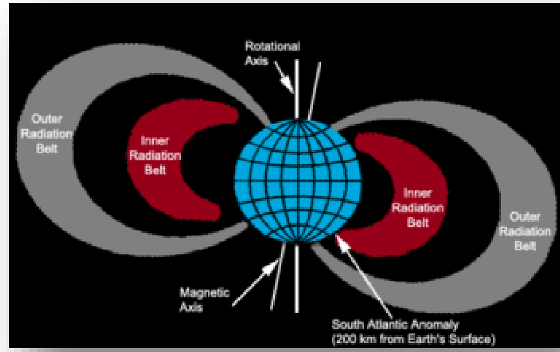


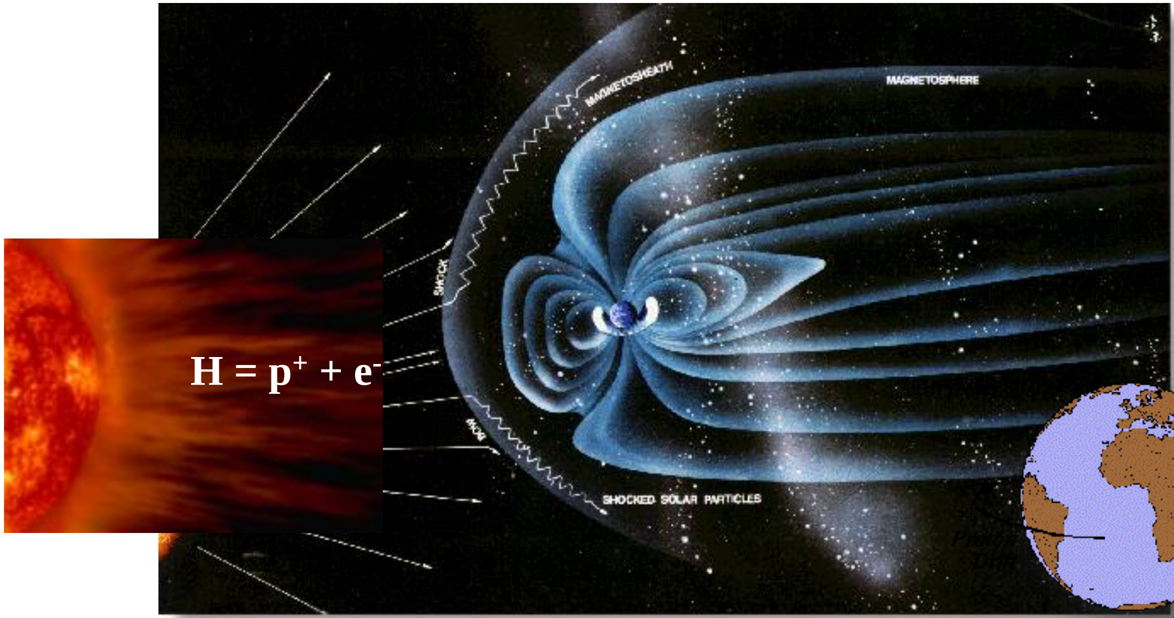
SOLAR CELL

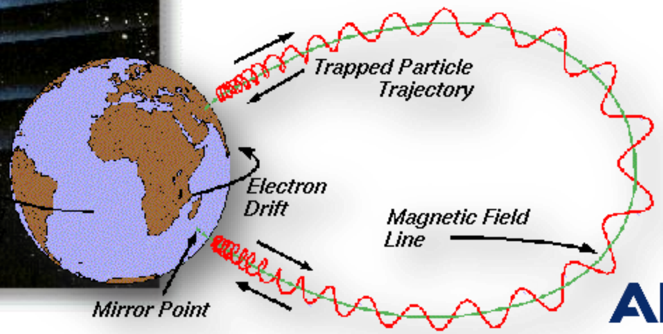
Radiation influence

- Protons and electrons from the Sun are trapped by Earth magnetic field and concentrated in radiation belts

→ degrades material properties
→ degrades solar cell performances
→ affects performance of electronics components







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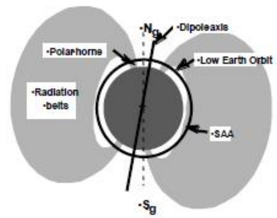
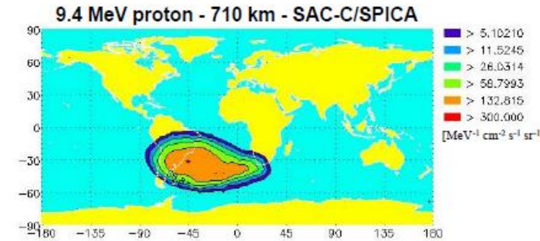
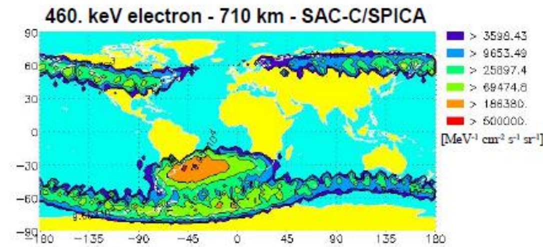
SOLAR CELL

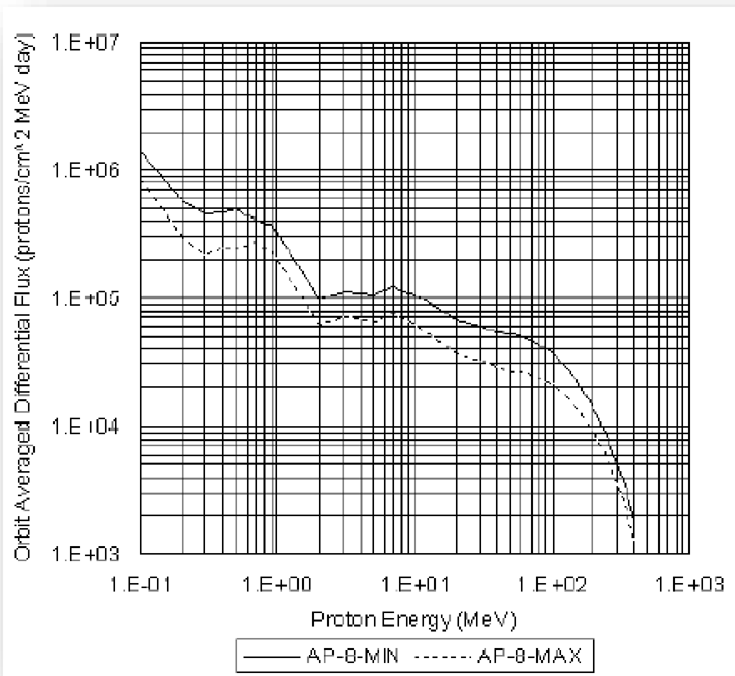
Radiation influence

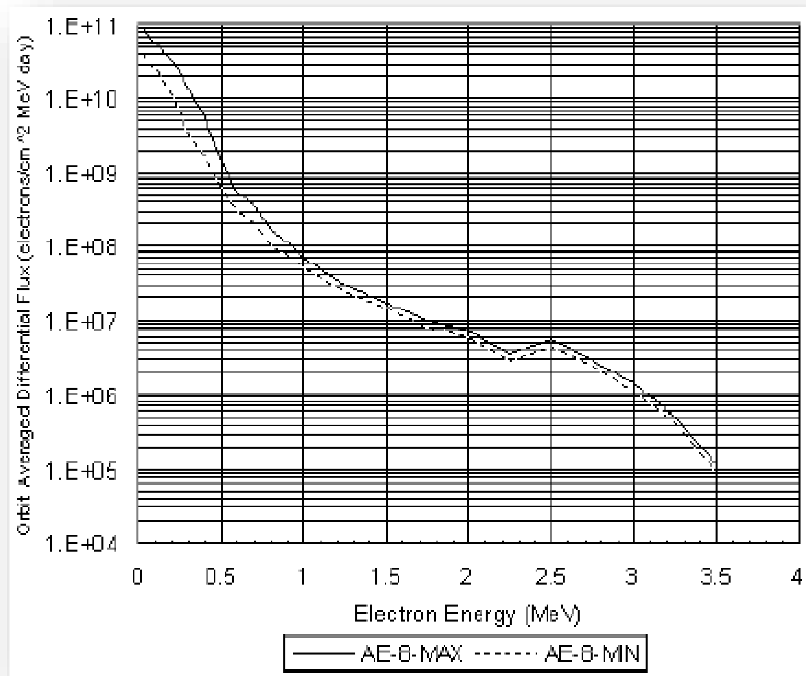






- Models are giving spatial repartition and energy distribution of electrons and protons
- AP-8 (protons) and AE-8 (electrons) models





SOLAR CELL

Radiation influence

The notion of **equivalent fluence**

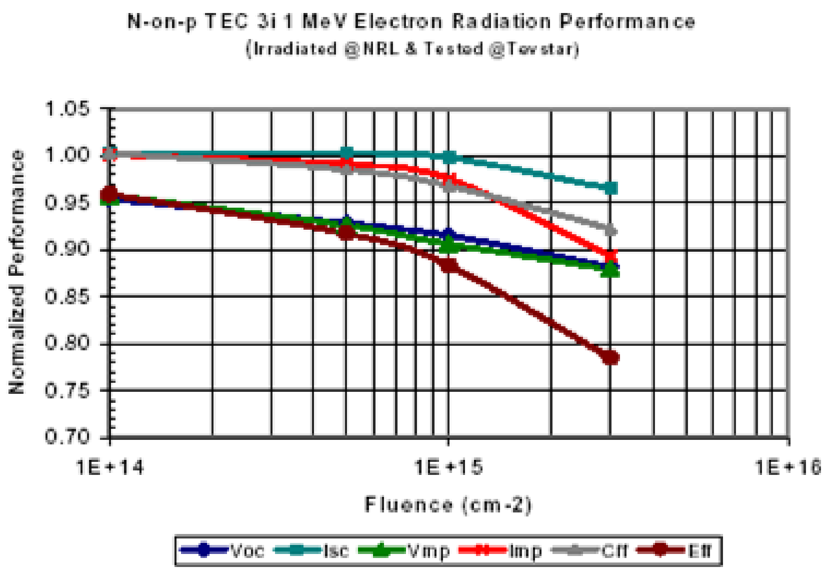
- It is not possible on ground to reproduce a given particular environment.
- In practice, we use electron guns, or more rarely, proton sources of determined energy.
- The equivalent fluence is therefore defined as the number of electrons (of 1MeV) or protons (of 10MeV) that can cause the same damage to the irradiated cell as the incident flow.
- The fluence depends on the composition of the cell and on the protection provided by the cover (in front face) and the support (in rear face).
- The “magic figures” allow converting the protons into electrons:
  – For example, a proton of 10MeV is equivalent to 3000 electrons of 1 MeV

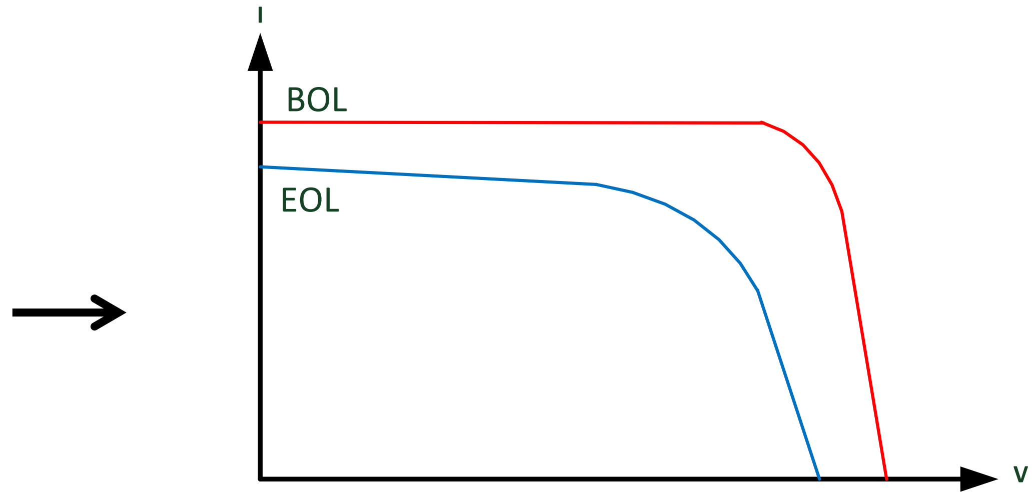
SOLAR CELL

Solar cell electrical parameters evolution according to radiation

Example of cell performances in irradiation → expressed in fluence of electron per cm²

- Benign on LEO orbits: 1e14
- Significant for GEO after electrical orbit raising: 1 to 5e15
- Extreme for MEO in the belt: 1e16





SOLAR CELL

Coverglass

- In order to **limit the performance loss caused by radiations,** a transparent cover is generally bonded to the cell. This **cover absorbs the lower energy particles** that contribute very significantly to the overall degradation

- The cell interconnector must be fitted to the cell before coverglass installation. The result is a CIC : Connector Integrated Cell. After cover installation, it becomes a **SCA : Solar Cell Assembly**

- A careful choice of the cover optical properties and anti reflective coating (ARC) **allows to safeguard the bare cell performance (and sometimes improve it)** ...

- ... but the **adhesive used to bond the cover is slightly sensitive to UV radiations**, intense in the AM0 spectrum, which results into a small loss of transmittance and corresponding increase in operating temperature.

- In addition, micrometeoroids and man made debris, especially in LEO, are responsible for some level of cover erosion (especially ARC), with similar consequences.

SOLAR CELL

Typical performances

- Silicon

Parameter	Abbreviation	Typical value BSR	Typical value HiEta	Unit
Short circuit current	Isc	40	44	mA/cm²
Open circuit voltage	Vco	600	625	mV
Maximum power	Pmax	18	21.3	mW/cm²
Intensity at Pmax	Im or Imax	37	41	mA/cm²
Voltage at Pmax	Vm or Vmax	480	520	mV
Form factor	FF	0.74	0.78	
Efficiency		13	16	%

- Gallium Arsenide

Parameter	Abbreviation	Typical value Single junction	Typical value Triple junction	Unit
Short circuit current	Isc	31	17	mA/cm²
Open circuit voltage	Vco	1000	2600	mV
Maximum power	Pmax	25	37	mW/cm²
Intensity at Pmax	Im or Imax	30	16	mA/cm²
Voltage at Pmax	Vm or Vmax	850	2350	mV
Form factor	FF	0.82	0.85	
Efficiency		19	27.5	%

ATTENTION:

Valid under normalised flux and temperature!!

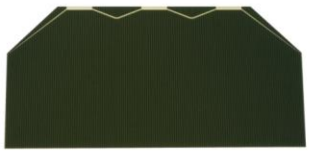
AIRBUS

DEFENCE AND SPACE

SOLAR CELL

How to read a datasheet?

32% Quadruple Junction GaAs Solar Cell
Type: QJ Solar Cell 4G32C - Advanced



Design and Mechanical Data

Base Material	AlInGaP/AlInGaAs/InGaAs/Ge on Ge
AR-coating	TiO_x/Al_2O_3
Dimensions	40 x 80 mm ± 0.1 mm
Cell Area	30.18 cm^2
Average Weight	≤ 1780 mg (*≤ 2600 mg)
Thickness	110 ± 12 µm (*150 ± 20 µm)
Contact Metallization Thickness (Ag/Au)	4 – 6.2 µm

*available alternative version

Electrical Data (typical)

		BOL	5E14	1E15	3E15	1E16
Average Open Circuit V_{oc}	[mV]	3451	3292	3227	3120	2955
Average Short Circuit I_{sc}	[mA]	457.6	453.3	451.5	423.8	365.1
Voltage at max. Power V_{mp}	[mV]	3025	2866	2793	2700	2581
Current at max. Power I_{mp}	[mA]	433.5	428.0	423.8	394.0	320.9
Average Efficiency η_{bare} (1367 W/m^2)	[%]	31.8	29.7	28.7	25.8	20.1

Standard: PS_4G32_PTB_2016-09-13; Spectrum: AM0 WRC = 1367 W/m^2; T = 25 °C @fluence 1MeV [e/cm^2]

Acceptance Values (typical)

Voltage V_{op}	2900 mV
Min. average current $I_{op\ avg}$ @ V_{op}	438 mA
Min. individual current $I_{op\ min}$ @ V_{op}	418 mA

Temperature Gradients (typical)

			BOL	5E14	1E15	3E15	1E16
Open Circuit Voltage	$\Delta V_{oc}/\Delta T\uparrow$	[mV/°C]	- 8.4	- 8.8	- 8.9	- 9.1	- 9.5
Short Circuit Current	$\Delta I_{sc}/\Delta T\uparrow$	[mA/°C]	0.07	0.14	0.14	0.25	0.34
Voltage at max. Power	$\Delta V_{mp}/\Delta T\uparrow$	[mV/°C]	- 8.6	- 9.0	- 9.0	- 9.3	- 9.8
Current at max. Power	$\Delta I_{mp}/\Delta T\uparrow$	[mA/°C]	0.03	0.07	0.07	0.24	0.46

@fluence 1MeV [e/cm^2]

Threshold Values

Absorptivity	≤ 0.91 (with CMX 100 AR)
Pull Test	> 1.6 N at 45° welding test
Status	Qualified

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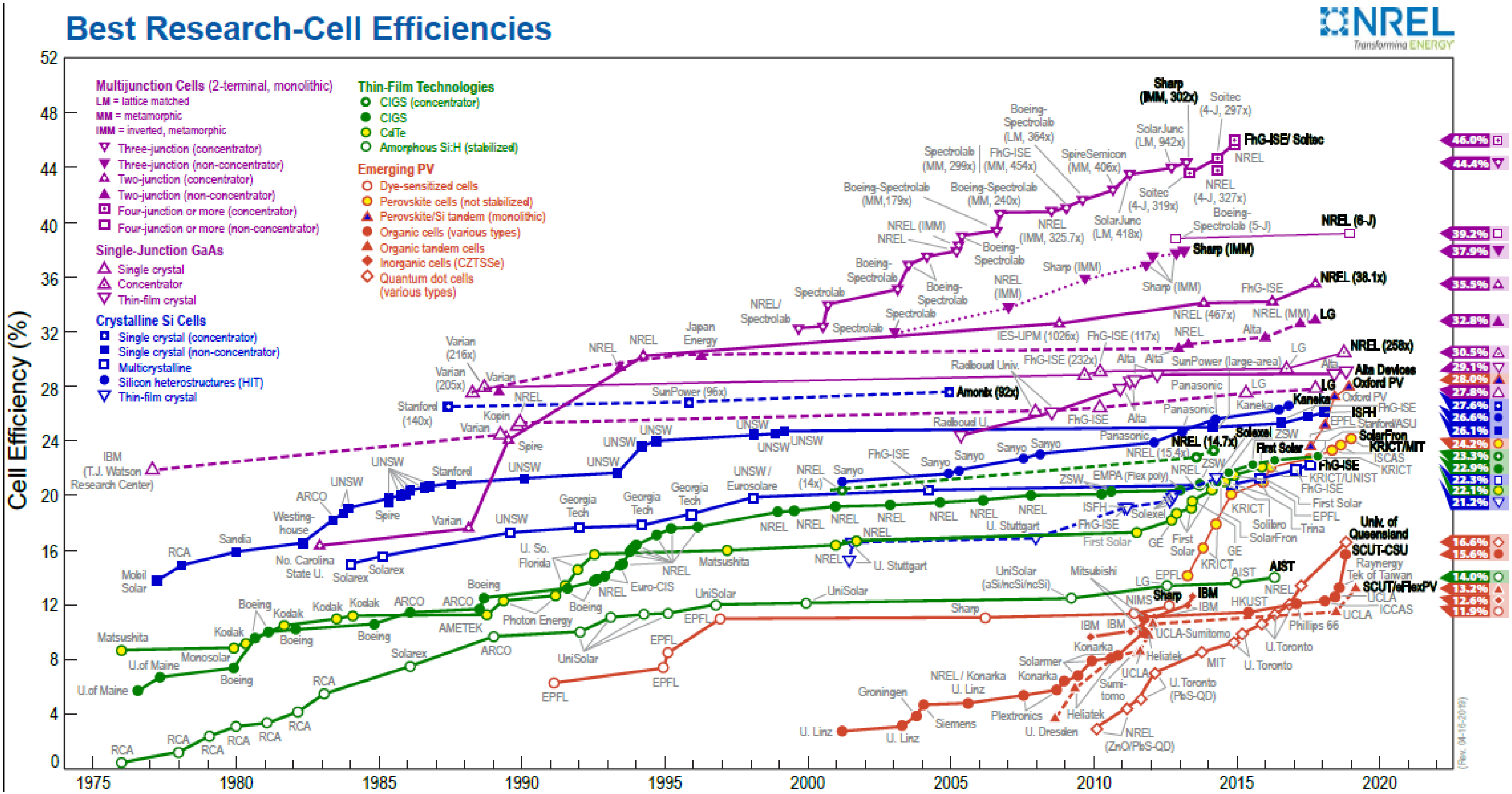
Best Research-Cell Efficiencies
NREL
Transforming ENERGY
Cell Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Perovskite/Si tandem (monolithic)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
(various types)
46.0%
44.4%
39.2%
37.9%
35.5%
32.8%
30.5%
29.1%
28.0%
27.8%
27.6%
26.6%
26.1%
24.2%
23.3%
22.9%
22.3%
22.1%
21.2%
16.6%
15.6%
14.0%
13.2%
12.6%
11.9%
(Rev. 04-16-2019)

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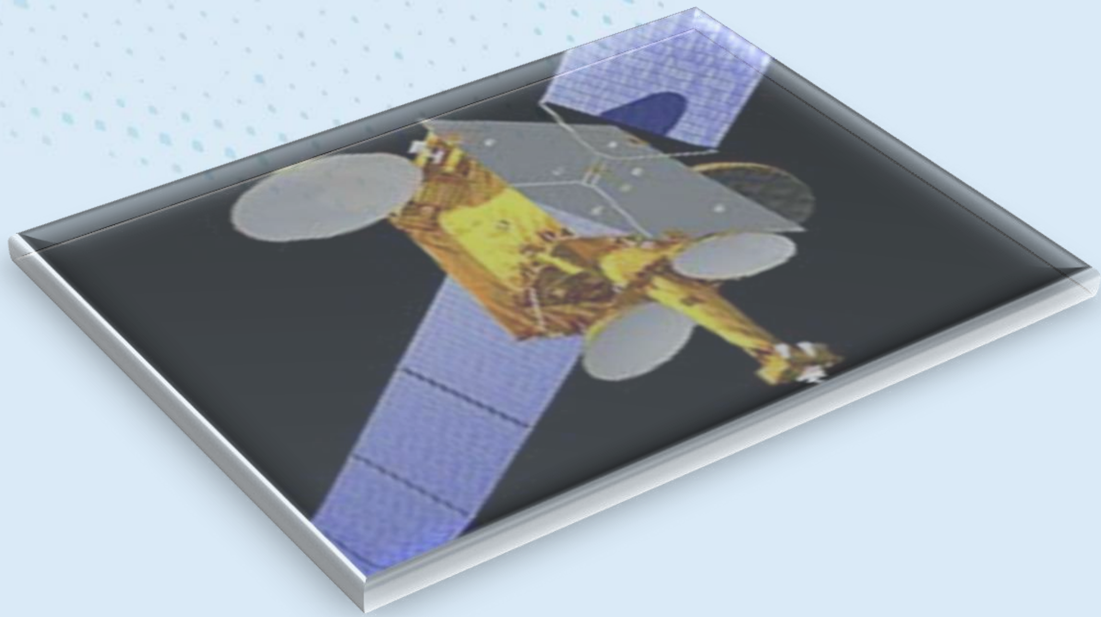
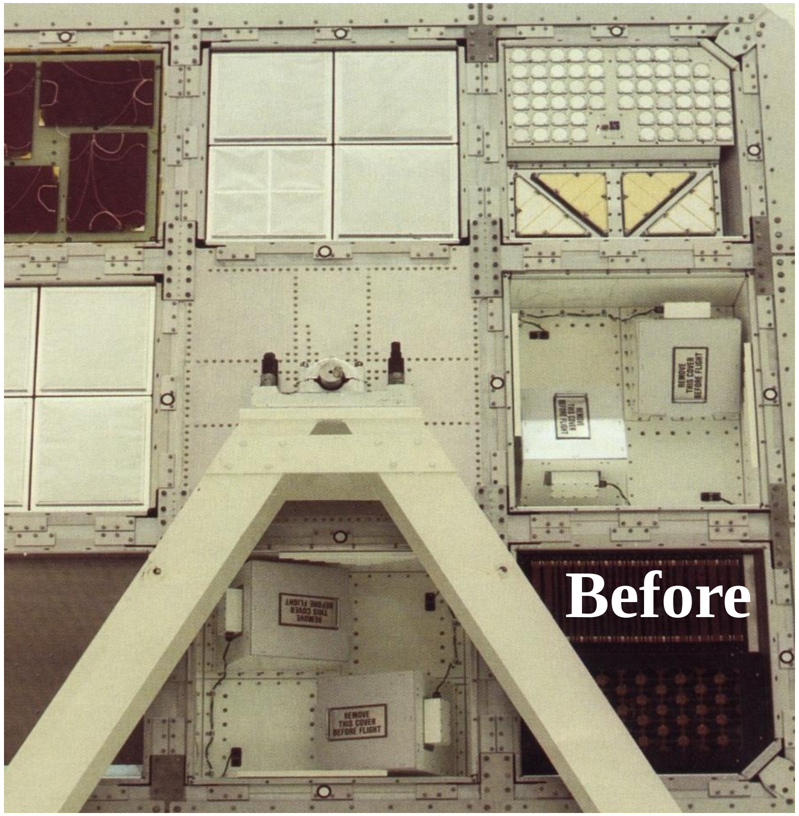
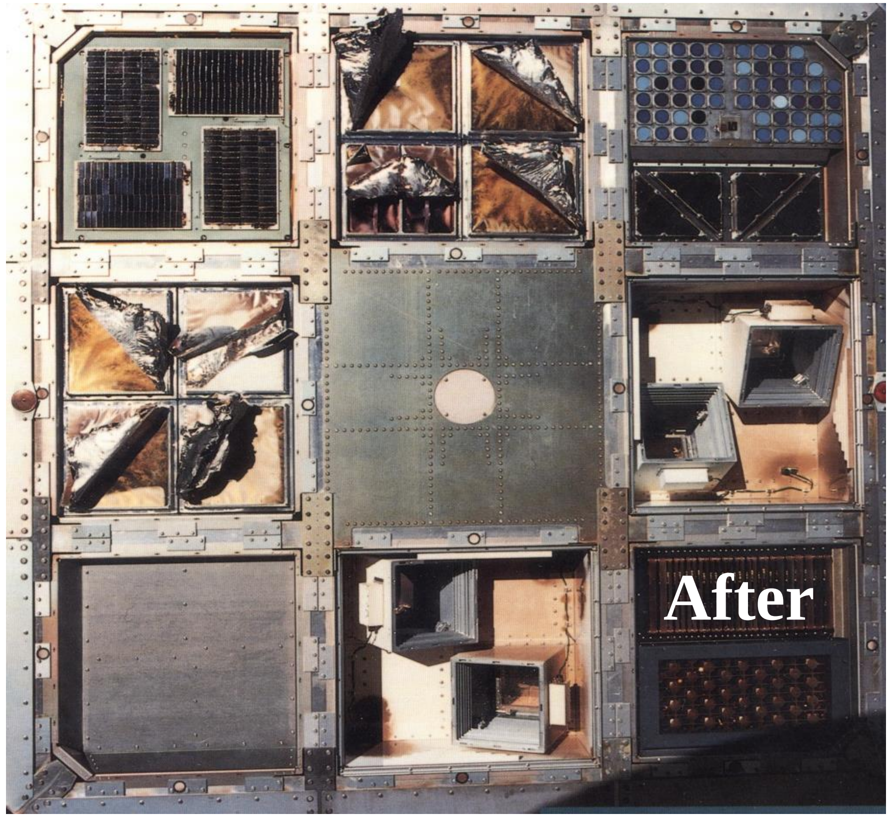
Coffee Break

SOLAR ARRAYS



Mission constraints on solar arrays





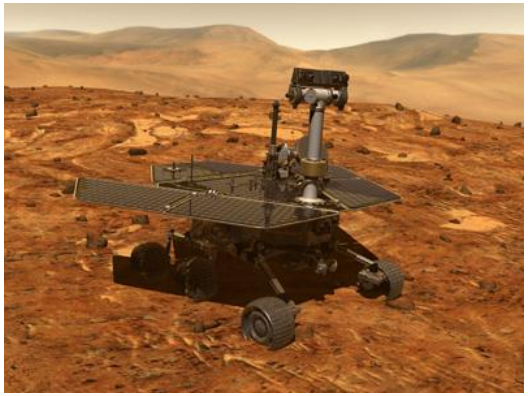
LDEF : Long Duration Exposure Facility

Mission constraints on solar arrays

- Launcher
  - vibrations, acoustic on large panels → mechanical failures
- Space environment
  - UV, electrons, protons → electrical degradation of cells
  - Thermal cycling due to orbit → thermo elastic fatigue of assemblies, joints and interconnectors
  - Atomic oxygen → erosion
  - Electrostatic charge & discharge → short circuits
  - debris, micrometeorites → short circuits
- Spacecraft interaction
  - Shadowing → reverse voltage on cells
  - Thruster plume (chemical and electrical)→ erosion, contamination

Missions constraints on solar arrays: the orbit

- GEO
  - **High power** (8 to 30 kW), 1500 **thermal cycles (-180°C, +50°C),** radiations (trapped electrons)
- LEO
  - 150 W to 8 kW, **60 000 thermal cycles (-100°C, +100°C**), moderate radiations (trapped protons)
- MEO & GTO
  - intermediate cycling & temperature limits, high radiation fluencies (protons)
- Interplanetary
  - Low intensity-Low temperature or high intensity-high temperature
- Planetary
  - Low intensity, dust, atmospheric absorption



Mission constraints on solar arrays: atomic oxygen

- Definition
  - Atomic oxygen is a molecular specie composed of only one Oxygen atom
- Origin
  - Atomic oxygen at normal temperature is not thermodynamically stable
  - Atomic oxygen if formed by dioxygen dissociation under UV radiations

$$O_2 \underset{}{\overset{UV}{\rightleftharpoons}} 2\,O$$

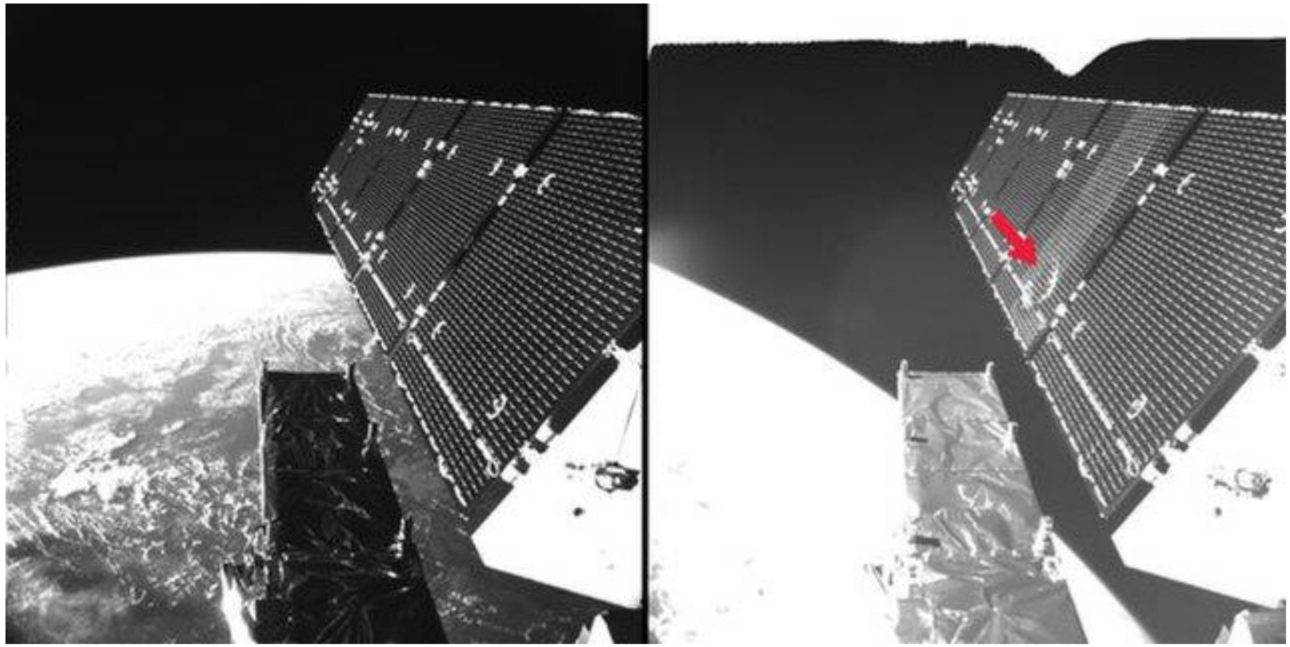
- Properties
  - Atomic oxygen is very reactive: it is a very strong oxidizers => Spacecraft damage
  - Atomic oxygen velocity is thermal velocity, but satellites move at 8km/s => 4.6eV atoms
- Localisation
  - Atomic oxygen only exists at low earth orbit

→ ***Degrades material properties on solar arrays***

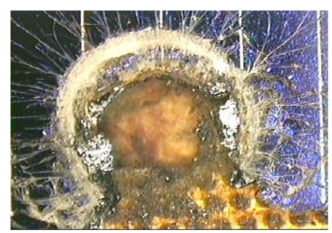
→ ***Affects solar array designs***

Micrometeorites and debris

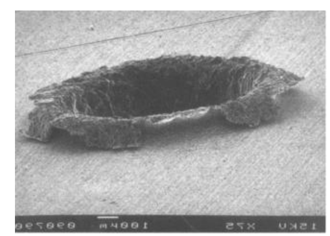
Sentinel -1A impact



Brittle



Ductile



→ ***Risk on solar arrays***

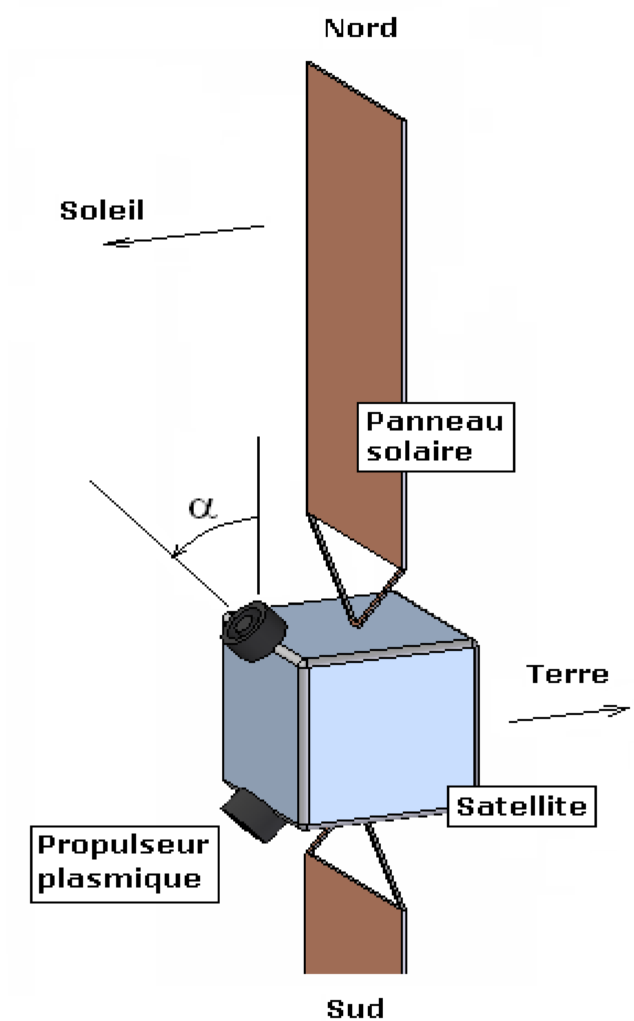
→ ***Risk on batteries and electronics mounted externally to structure***

Mission constraints on solar arrays: erosion

- Thruster erosion
  - Hall effect thruster: BN-SiO2
  - Gridded Ion Engine: Carbon, Molybdenum

- Solar array erosion
  - Interconnection metals (ex: Ag)
  - Cover-glasses
  - Borosilicate
  - Optical treatment (MgF2...)

- To be accounted in the solar array design



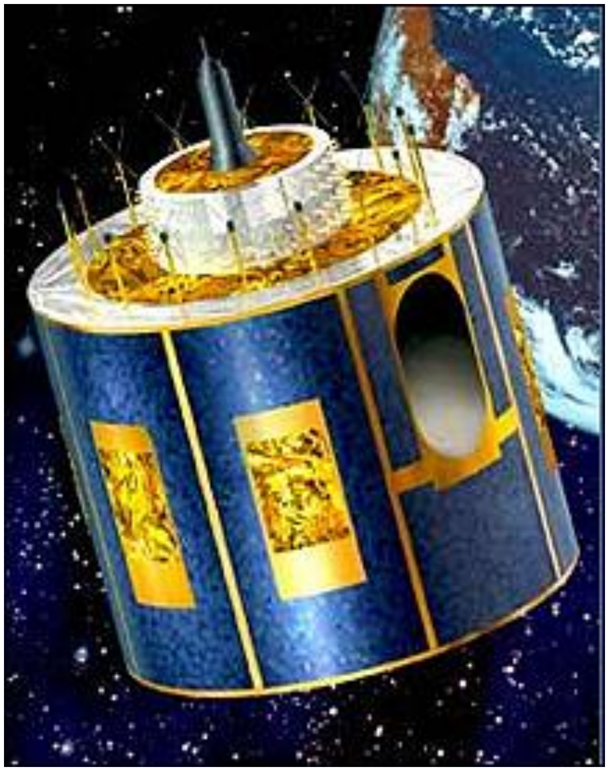
→ ***Degrades material properties on solar arrays***

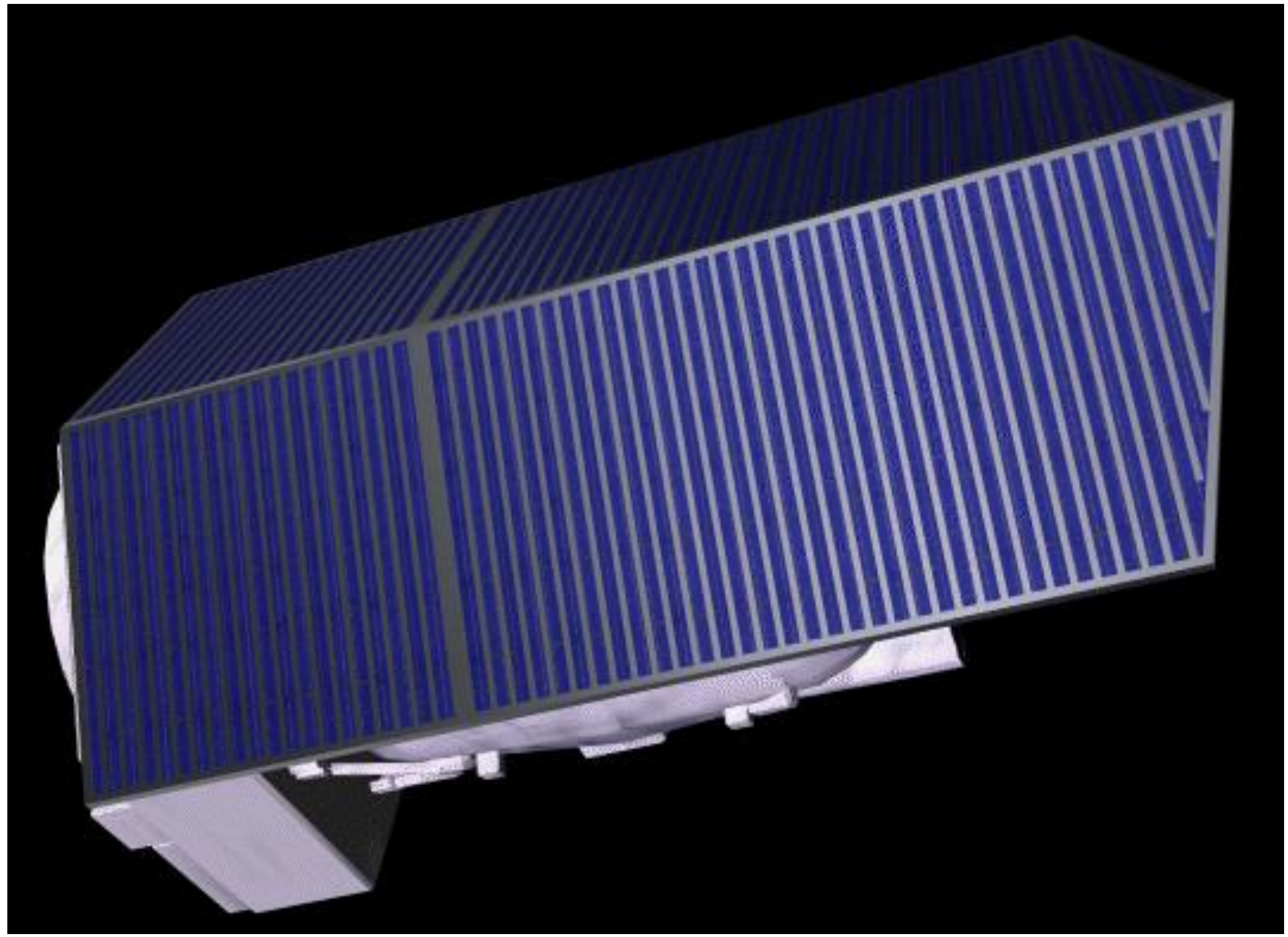
The solar array

- solar generator design is driven by mission need and constraints

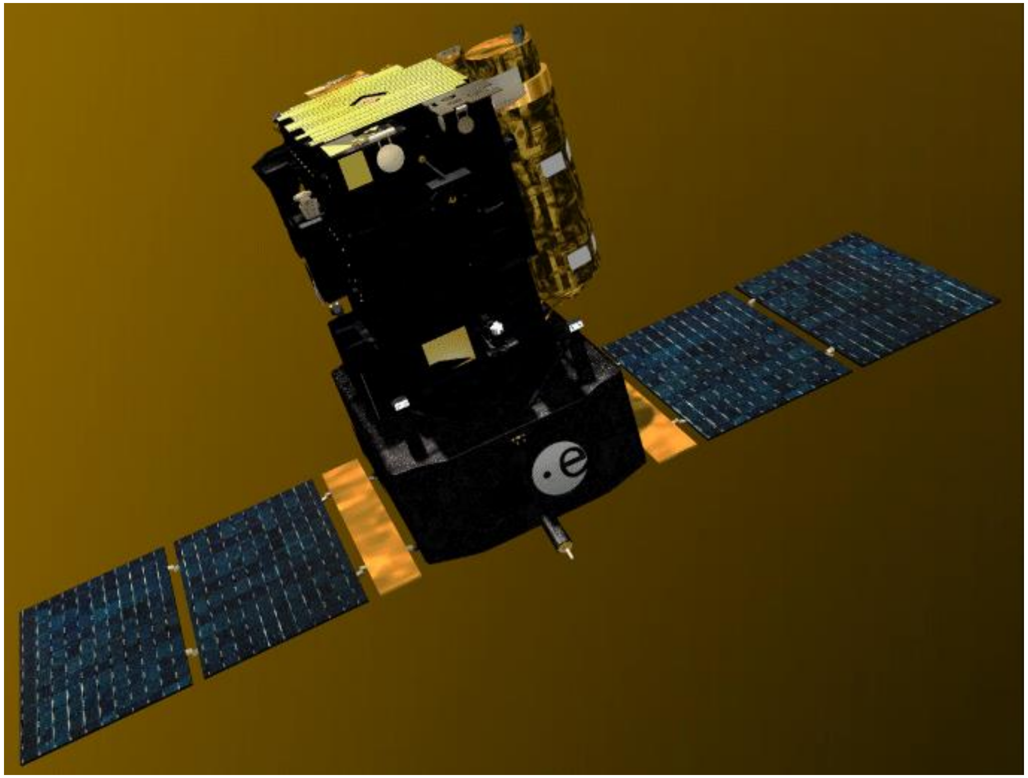
-try to figure out the cost of the solar generation…

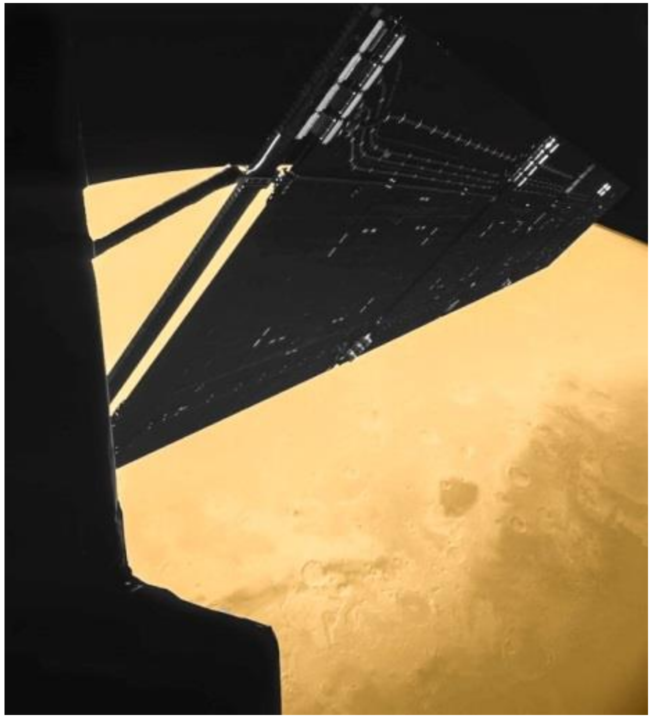
The solar array





The solar array





The solar array

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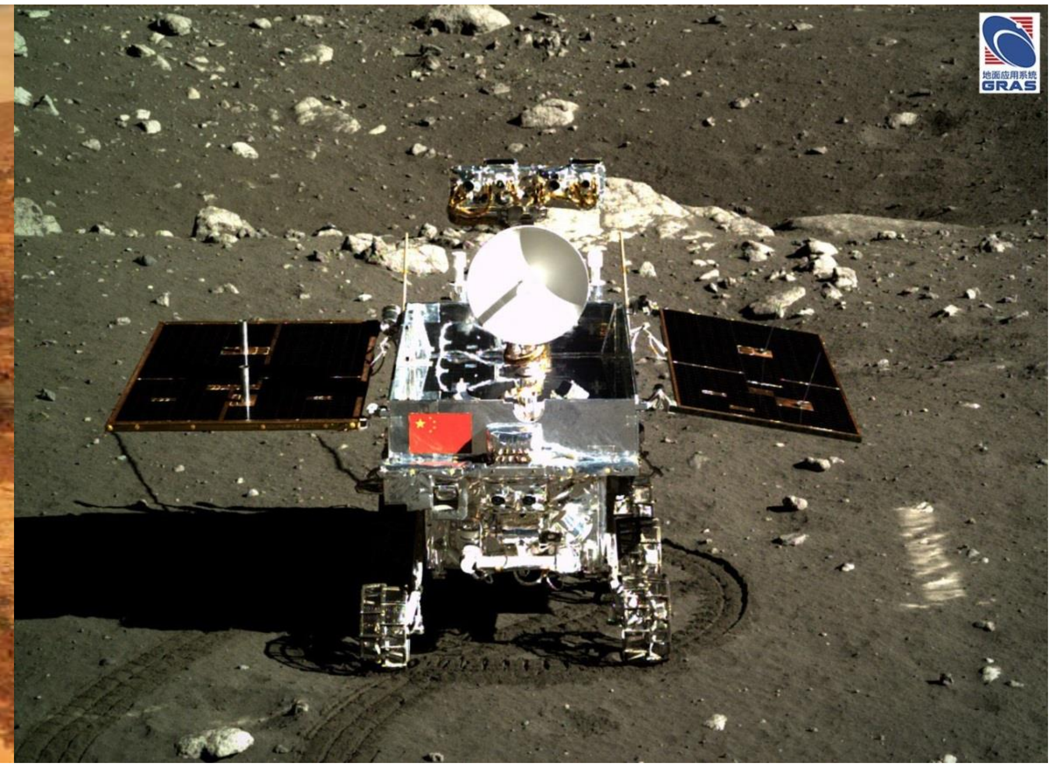
The solar array



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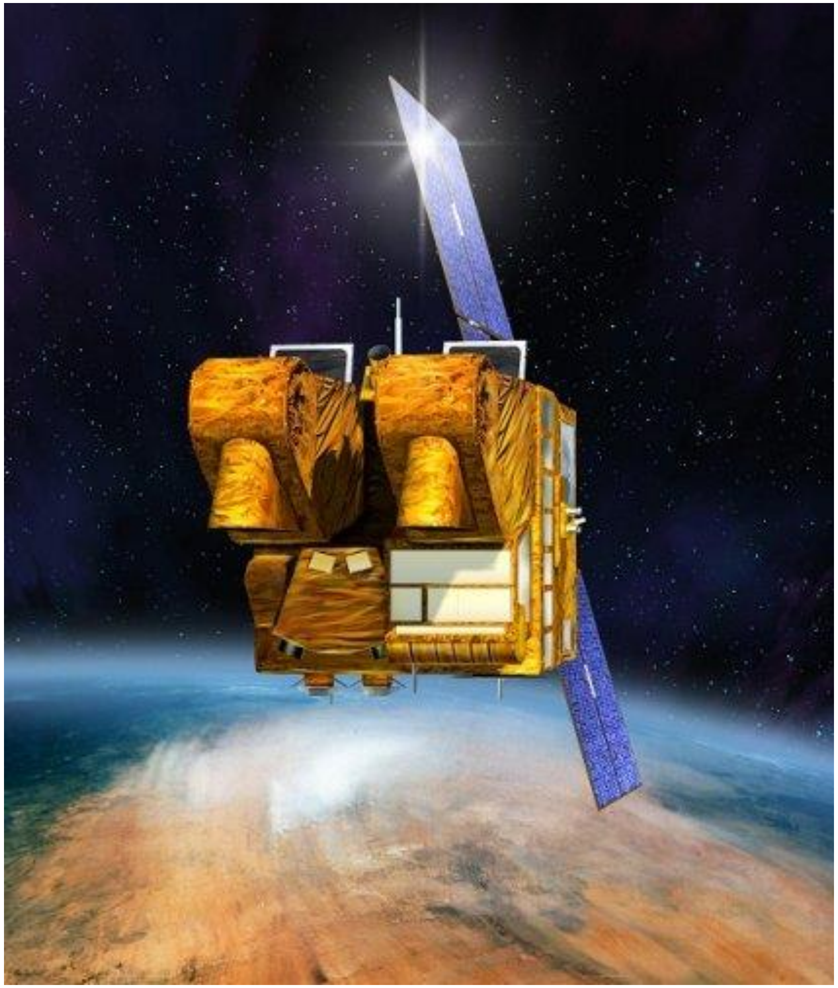
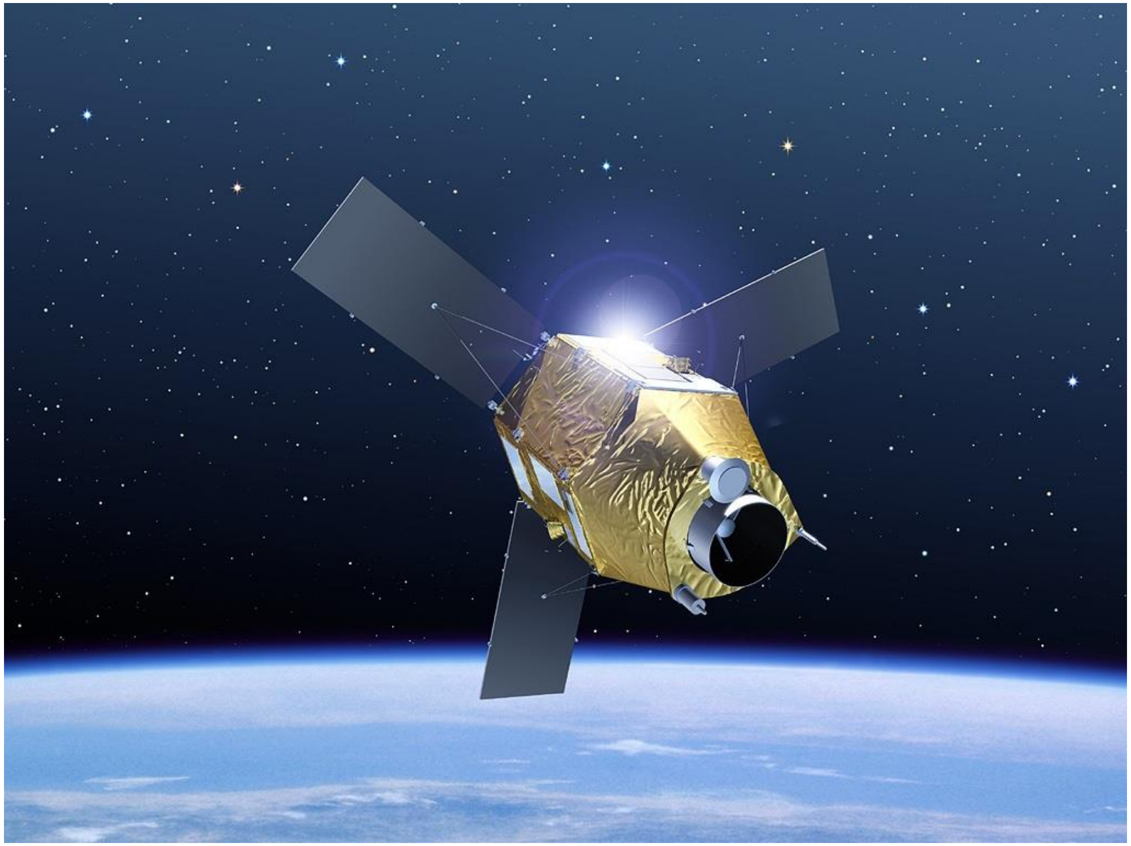
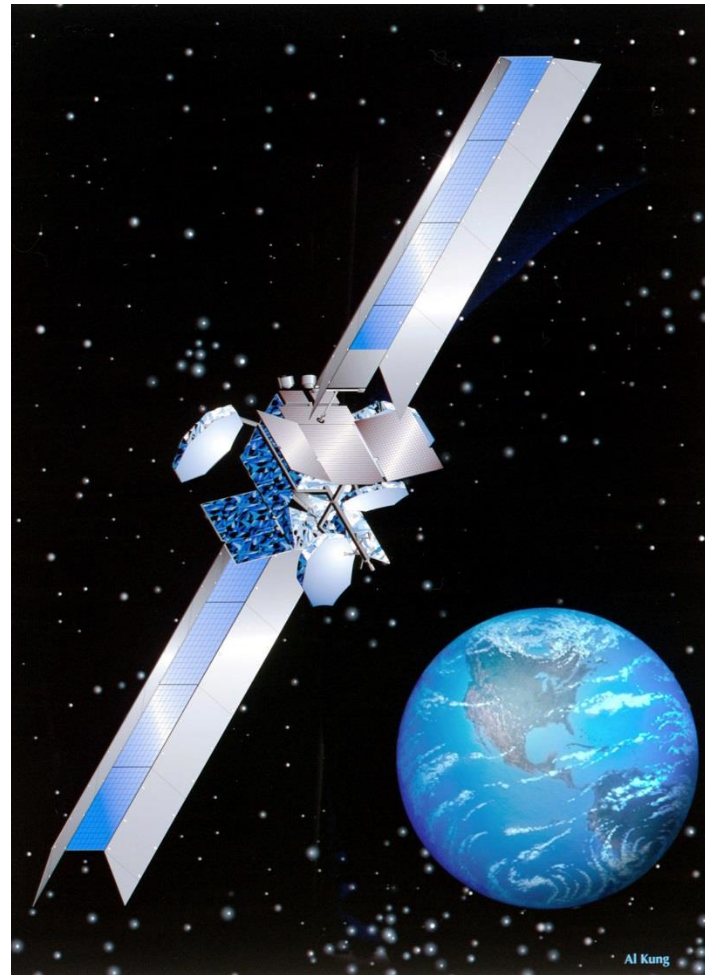
The solar array





The solar array



The solar array

The solar array

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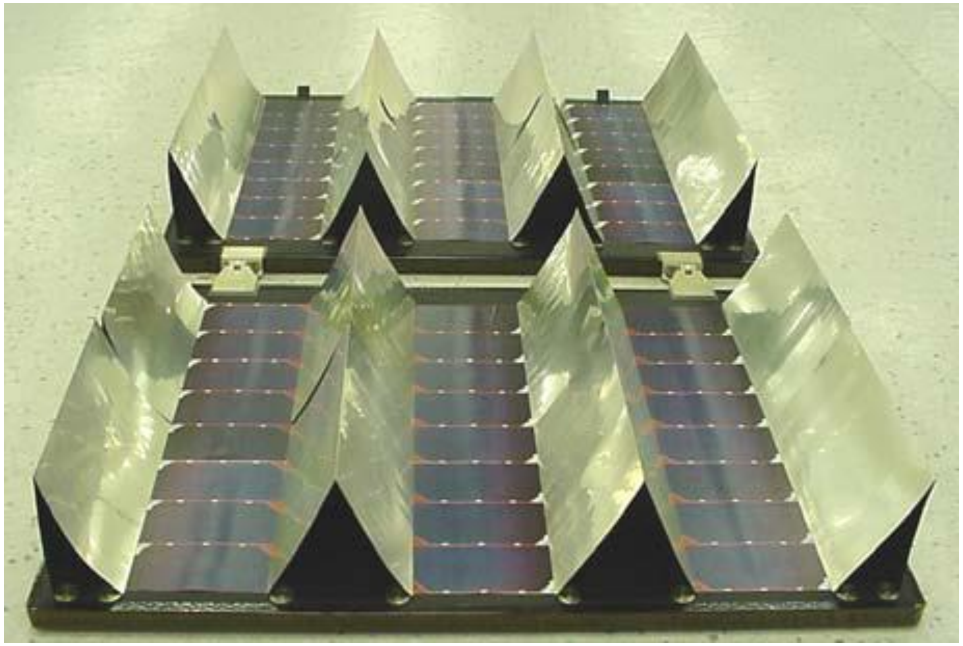
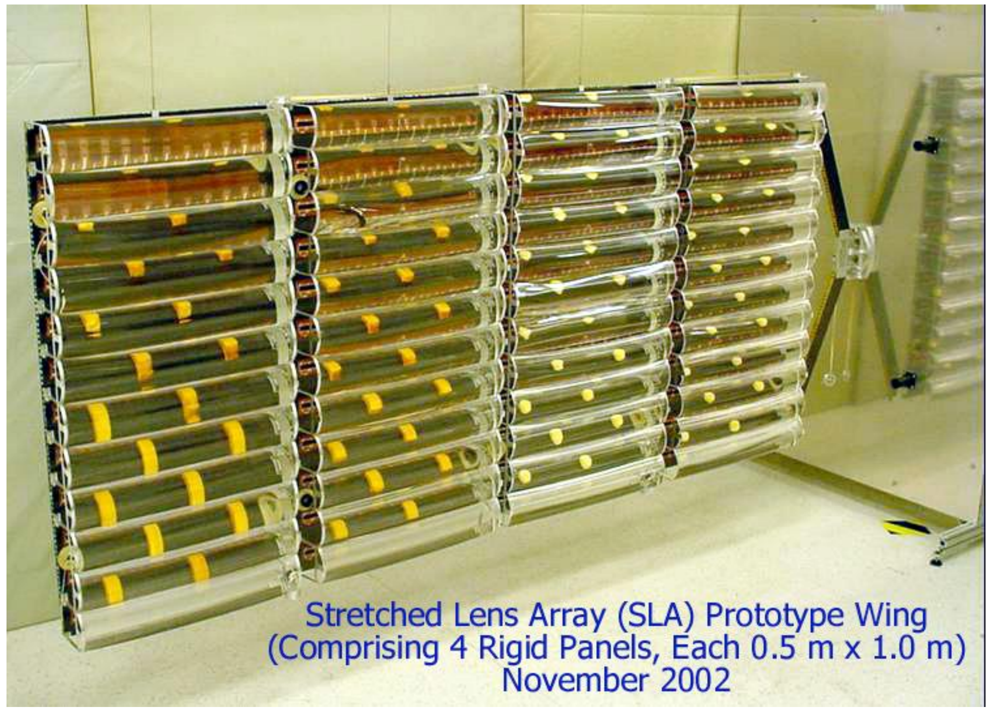
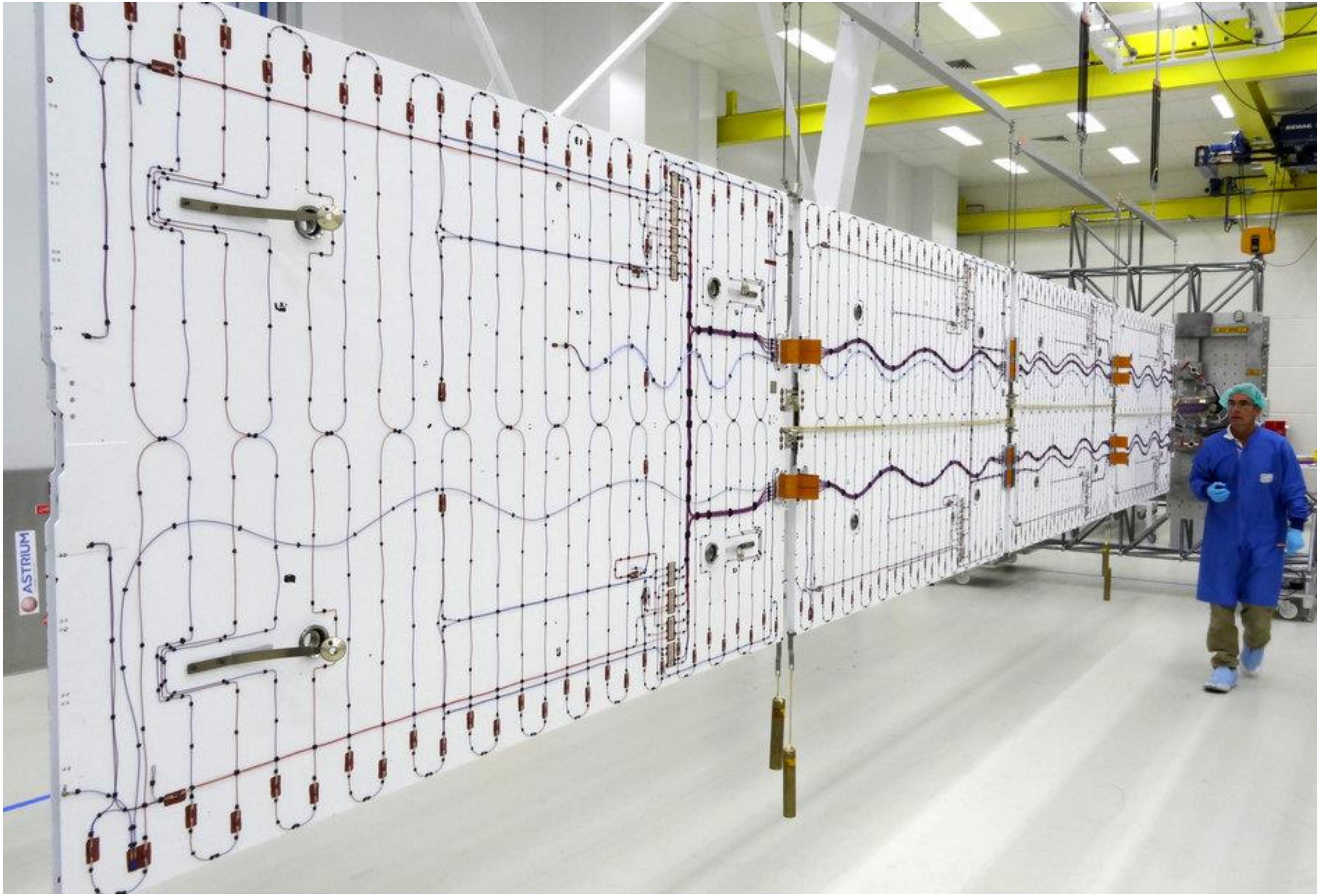
The solar array







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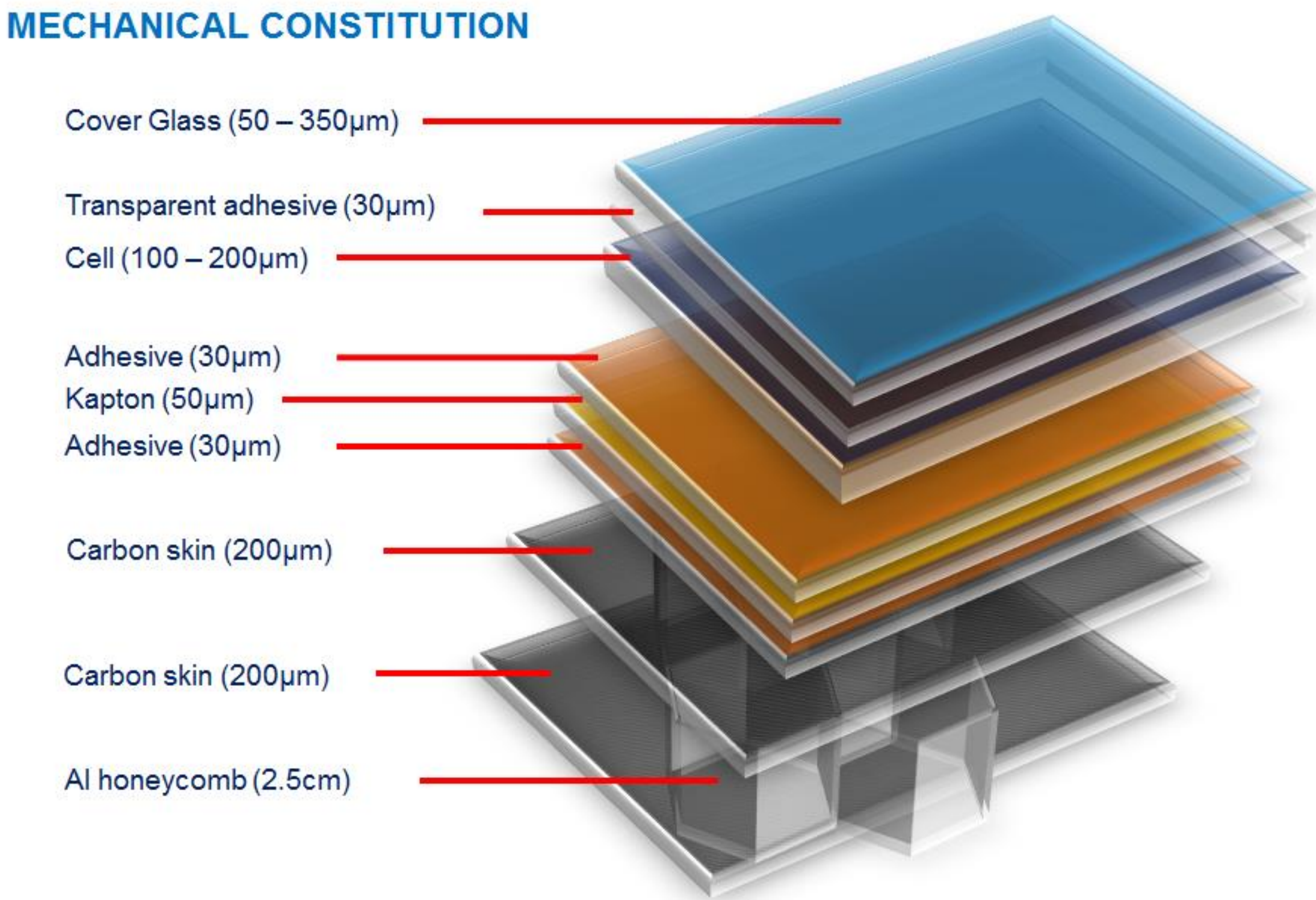
The solar array

Deployment videos

The solar array



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The solar array

Electrical assembly

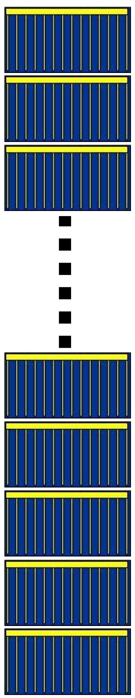
- **Terminology**
  - **String** = number of cells connected in series to get the desired voltage.
  - **Network** = all the solar array constituents that provide the electrical power supply function (includes the cells, interconnections, diodes and harness)
  - **Section** = part of the network that can be independently controlled by the electrical power system; in some cases (microsatellite, the network can be made by only one section)

The solar array

Electrical assembly

- **Objective n° 1 : to adapt the solar array to the operating voltage**

A string is by a series connection of a number of cells such that each one operates as close as possible to Vmp

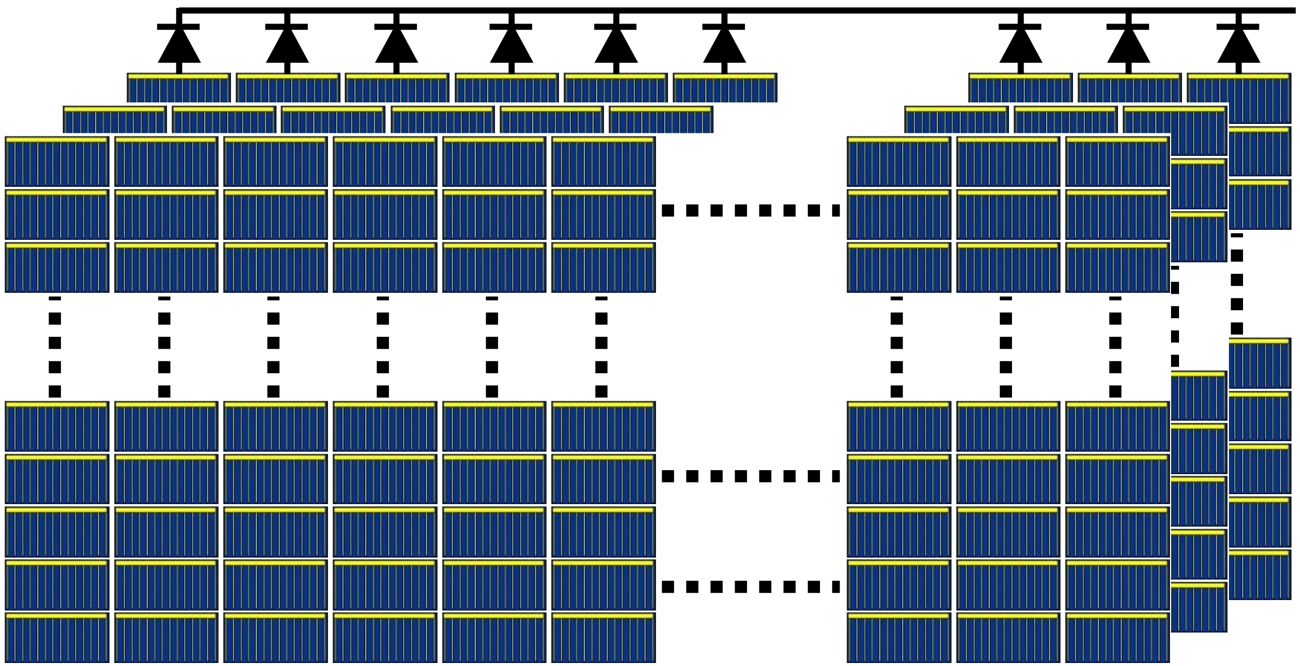


The solar array

Electrical assembly

- **Objective n° 2 : to adapt the solar array to the power need**

Then parallel connection of a number of string large enough to supply the requested current by 1 to n solar sections



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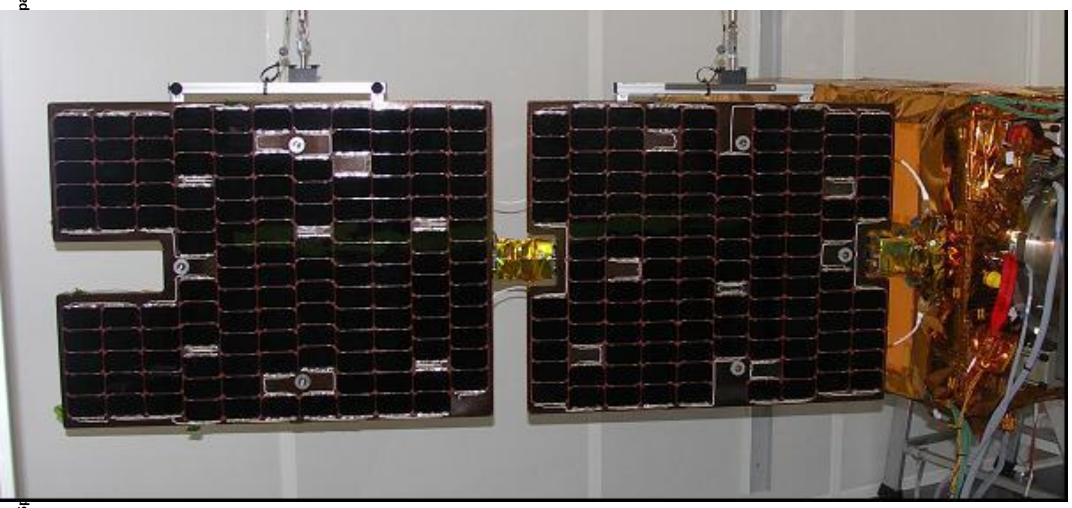
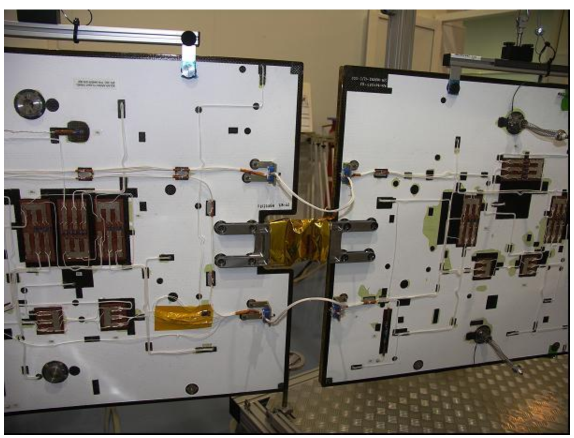
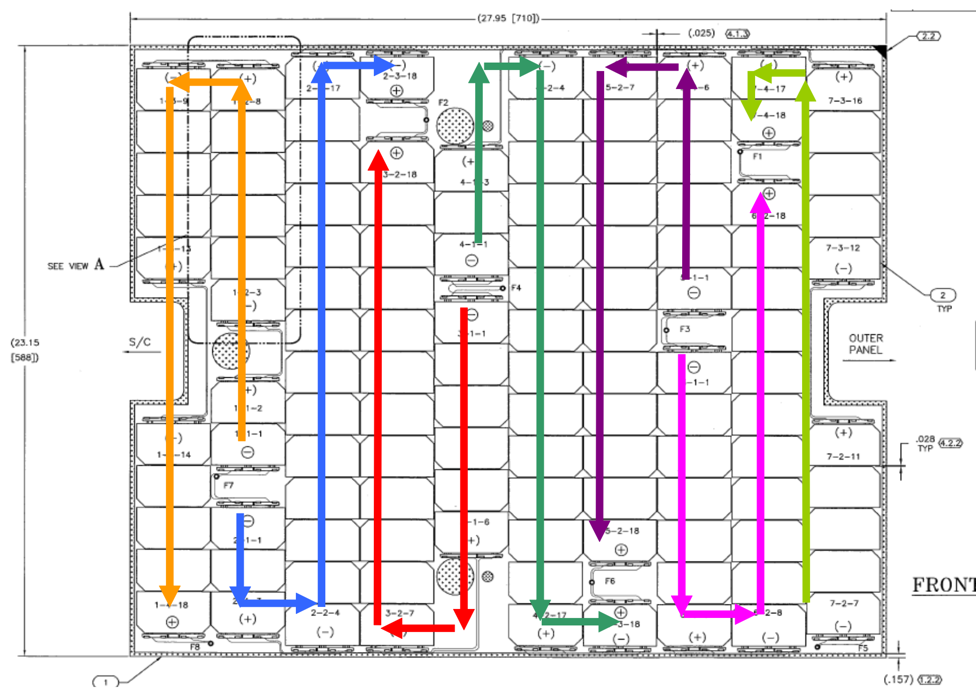
The solar array

Cells layout : example of micro-satellite







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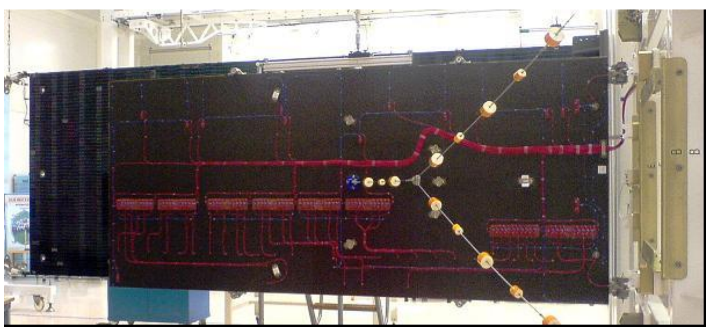
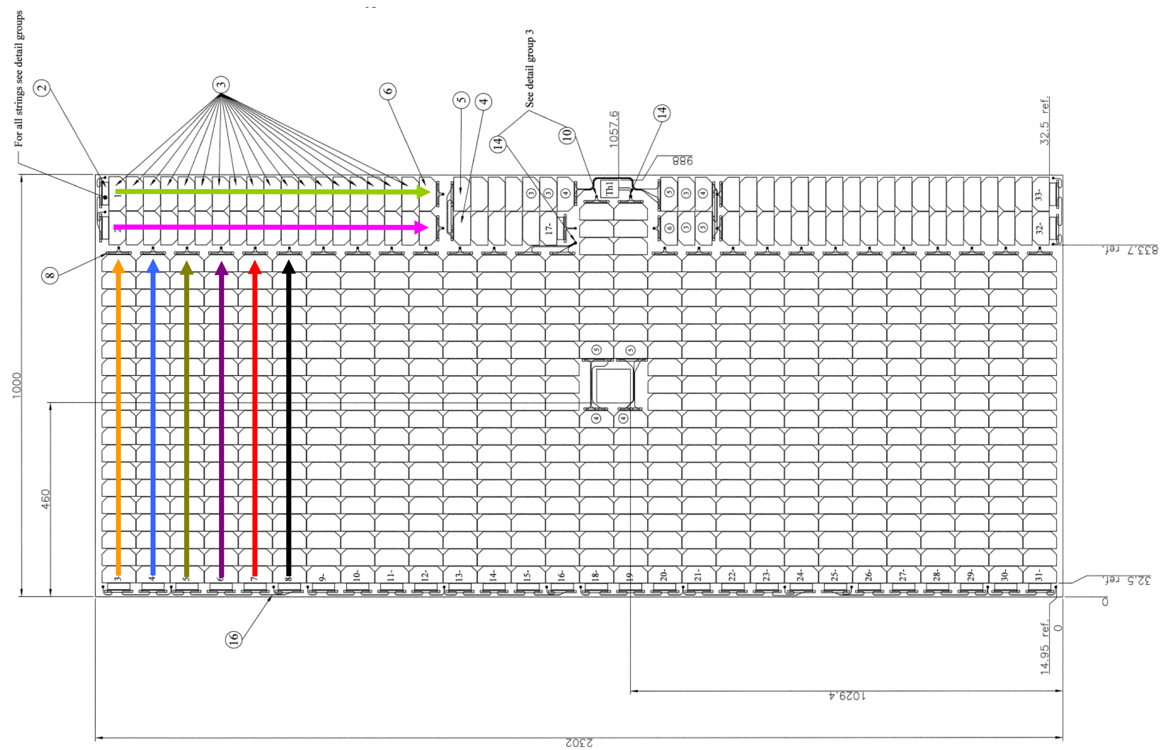
The solar array

Cells layout : example of Pléiades





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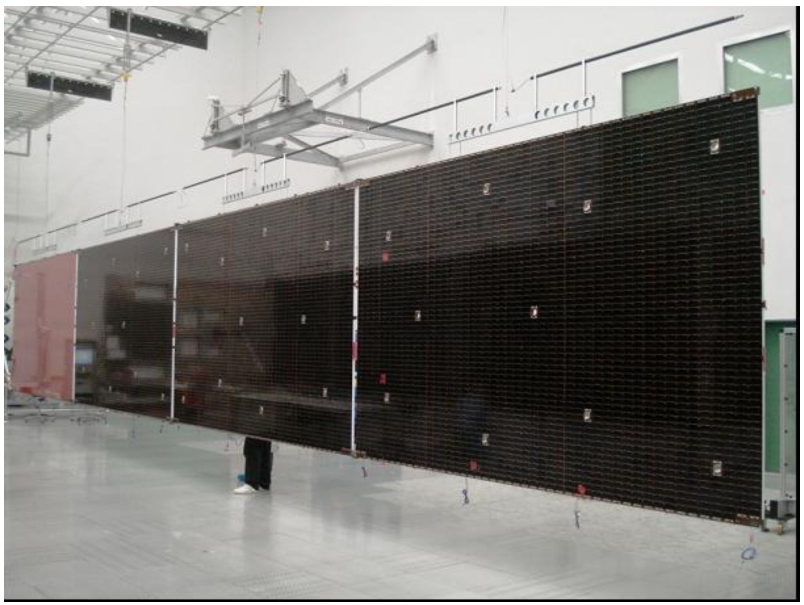
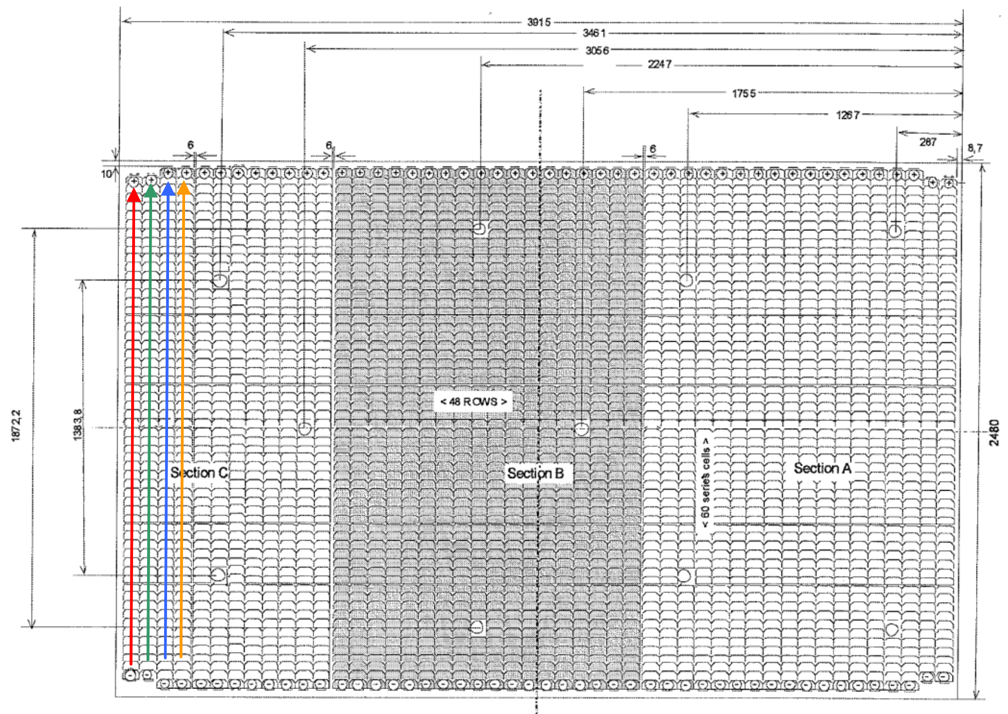
The solar array

Cells layout : example of Eurostar 3000



Panel P4 (Outboard)



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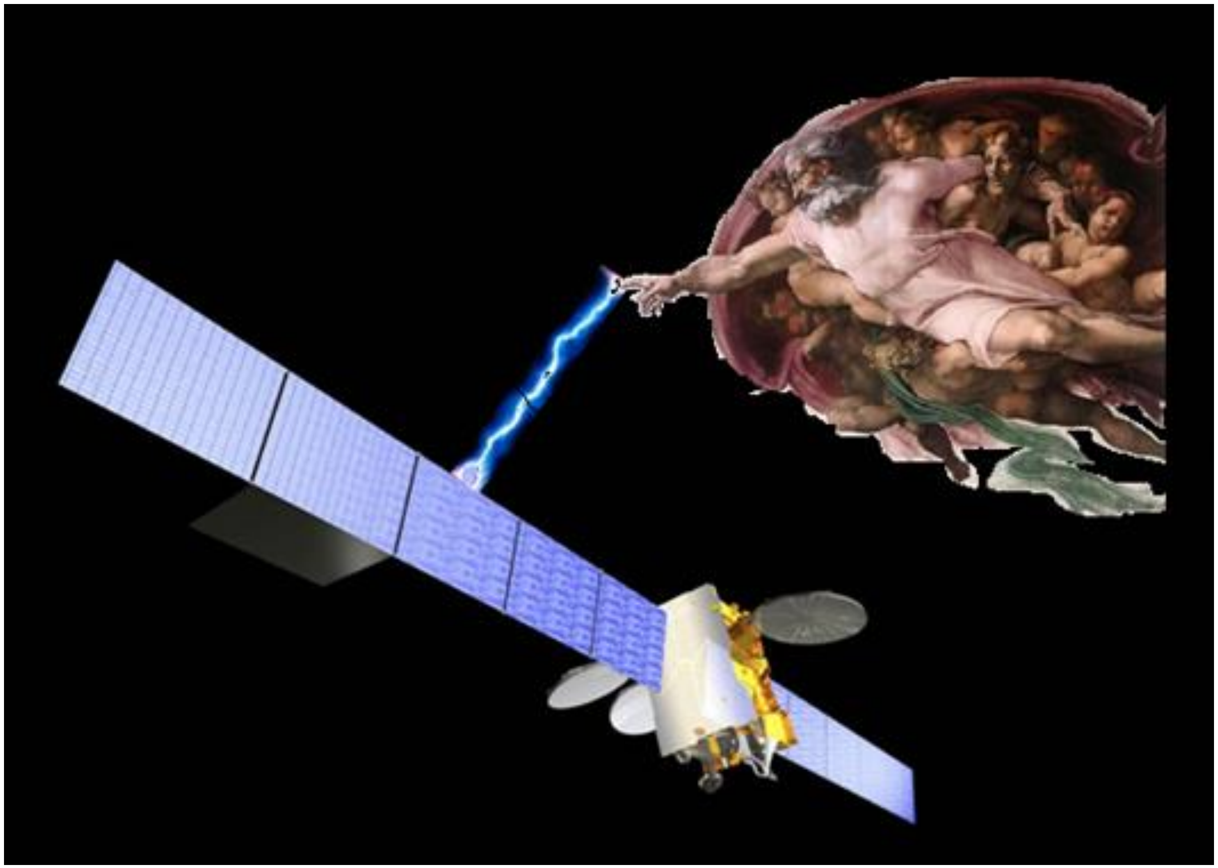
The solar array

Charging effect, electrostatic discharge

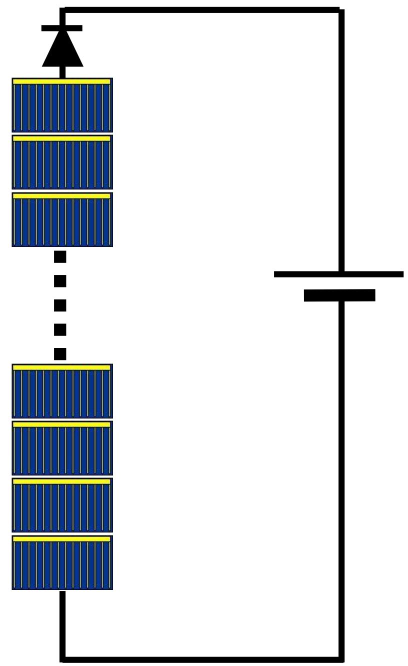


→ ***Affects solar array designs***

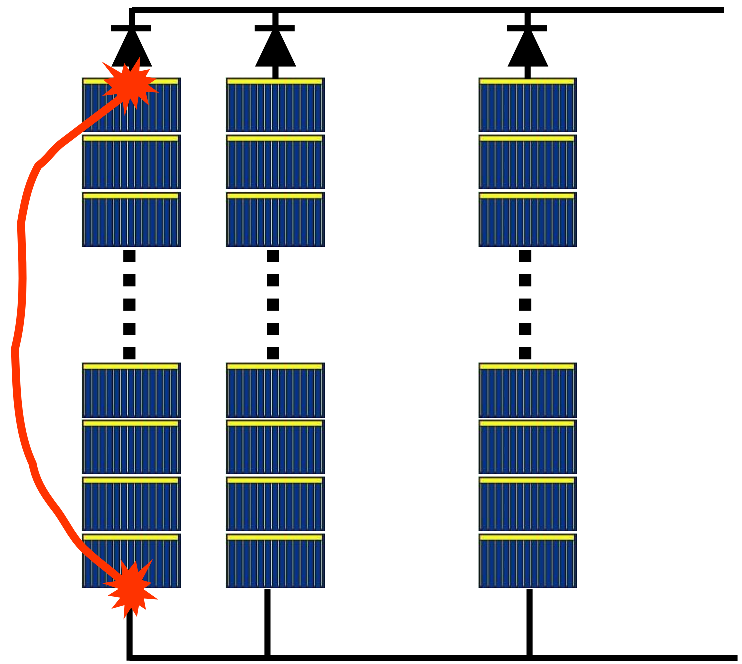
The solar array

Solar array blocking diodes

- **to prevent the battery from supplying the SA during eclipse**



- **to avoid propagating a string short circuit to the whole array**



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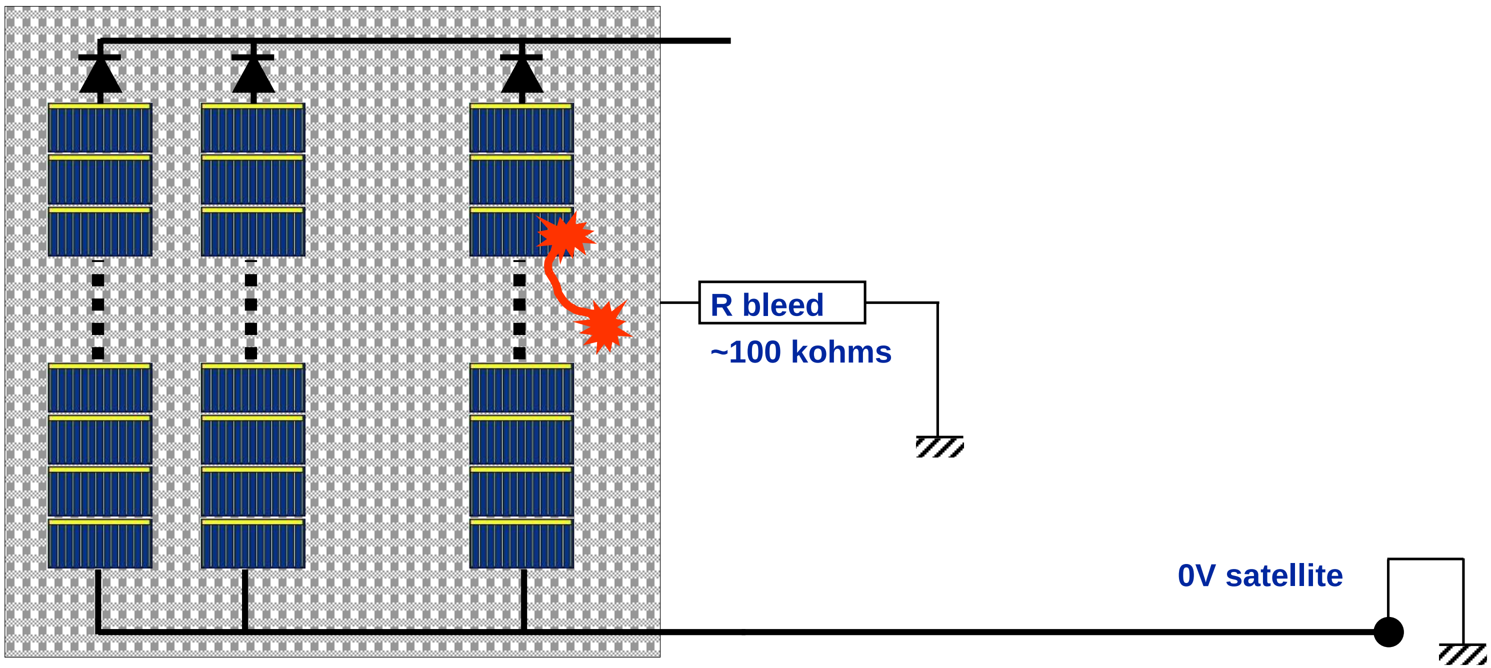
The solar array

ELECTRICAL CONSTITUTION: bleed resistors

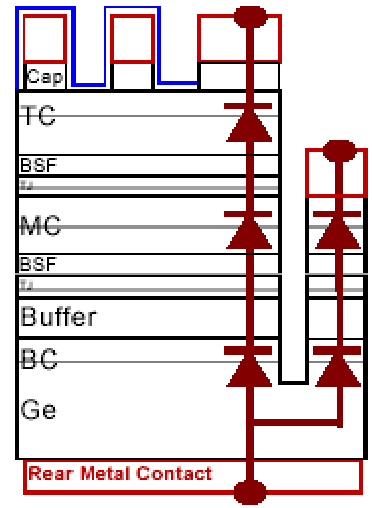
- to prevent failure propagation of a short circuit from the cell to the panel substrate

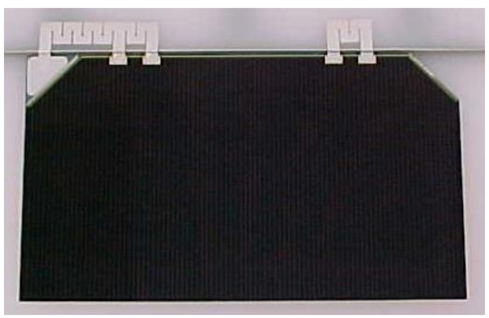


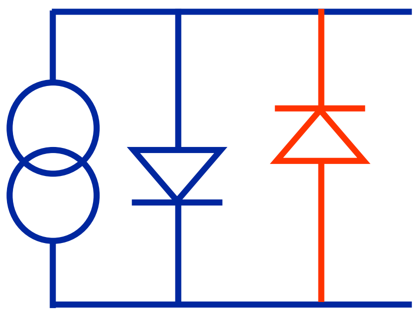
The solar array

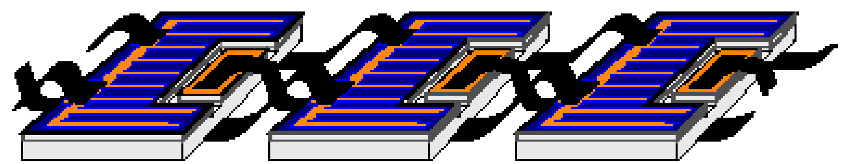
ELECTRICAL CONSTITUTION: by-pass diodes

- to protect solar cells from a hot spot due to shadowing by appendices
- to protect solar cells when a string is short-circuited by the power system
- the by-pass diode limits the reverse voltage applied to the cell in this cases



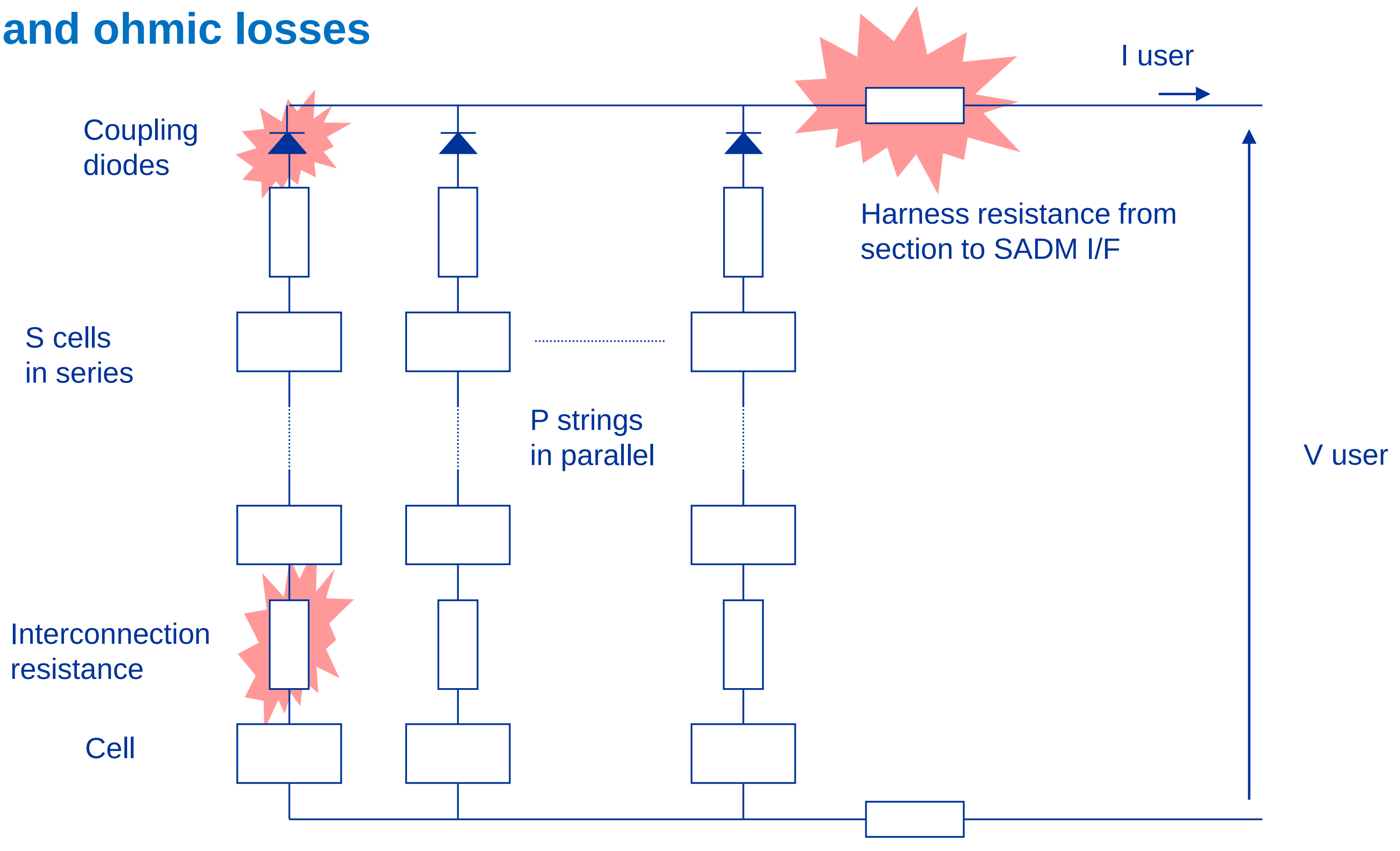






The solar array

Layout and ohmic losses



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The solar array

Loss factors

- Cell production, performance dispersion and measurement
  - Manufacturer data
  - Mismatch
  - Calibration
- Solar cell and array environment
  - UV
  - Micrometeorits
  - Radiation
- Solar array constituent reliability
- Other aspects of the mission may be included in the loss factor
  - Sun intensity
  - Sun angle
  - Temperature
  - Shadowing
  - Solar array pointing accuracy

	INPUT	POWER EOL (WORST CASE & STRING FAILURE)
(a)	Current Cell mismatch	0.99
(b)	Possibly better production	1
(c)	Calibration error	0.97
(i)	**Total RSS Calculation:** $Ground\_Loss = 1 - \frac{\sqrt{a^2+b^2+c^2}}{100}$	**0.968 (-3.2%)**
(j)	**Coverglass gain / loss**	**0.99 (-1%)** TBC by supplier
(d)	UV degradation and micro meteorites (total for EOL)	0.25%/year
(e)	Random Failure	1-1/(total number of string)
(h)	Pointing error due to disorientation and internal Solar Array error	TBD
(k)	**Total Calculation:** $Life\_Loss = d + e + f + g + h$	**TBD**
(l)	**Global Loss Factor:** $Loss\_Factor = 1 - \frac{j + \sqrt{i^2+k^2}}{100}$	**TBD**
	Radiation	Depending on mission environment
	Temperature	avg OP temperature on orbit +5°C margin to be included

The solar array

Solar array key figure of merits and key stakes

- Mass: from 7kg to 390kg / 1m² to 160m²
- Cost
- Development effort
  - Mechanical loads during launch
  - Mechanical load in orbit (thrusters)
  - Solar cell radiation hardness
  - Specific and bespoke EMC requirement
  - ESD aspects
- Qualification effort
  - Not completely qualified in representative condition…
  - Solar cells qualification (TAT)
  - Thermal cycling qualification (DVT coupon)
  - Deployment verification (MGSE and configurations)
  - Low temperature qualification (<-170°C)
- Low cost solar array R&T
  - Change solar array paradigm

The solar array

Solar array manufacturer

- In Europe : Airbus DS (Ottobrunn and Leiden), Thales Alenia Space (Cannes), SpaceTech (Immenstad, Germany)
- In the USA : each prime contractor has its own capacity for solar array design and manufacturing, (Lockeed Martin, NGIT)
- In Japan: MELCO (Mitsubishi)

Solar cells manufacturer

- In Germany : ISE (Fraunhofer): R&D, Azur Space (ex AeG, Telefunken, DASA, ASE, RWE): Si AsGa multi-junction
- In the USA : Spectrolab (Si, AsGa), SolAero (AsGa)
- In Japan : Sharp (Si, AsGa)

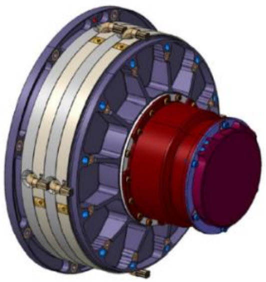
Photovoltaïc assembly manufacturer

- In Europe : Astrium DS (Ottobrunn), Leonardo (Milan)
- In the USA : Spectrolab, SolAero…
- In Japan : MELCO (Mitsubishi)

Solar array drive mechanism (SADM)

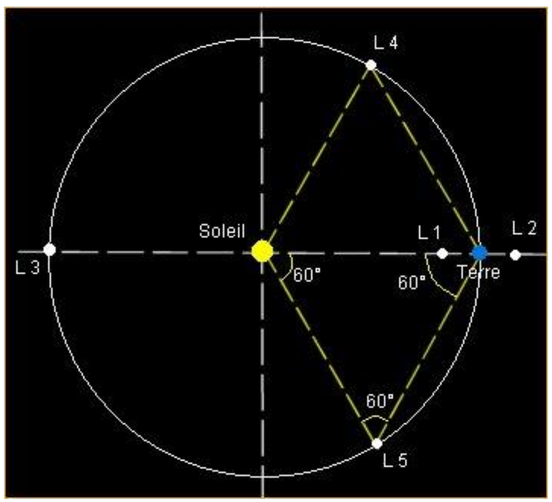
Solar array drive mechanism (SADM)

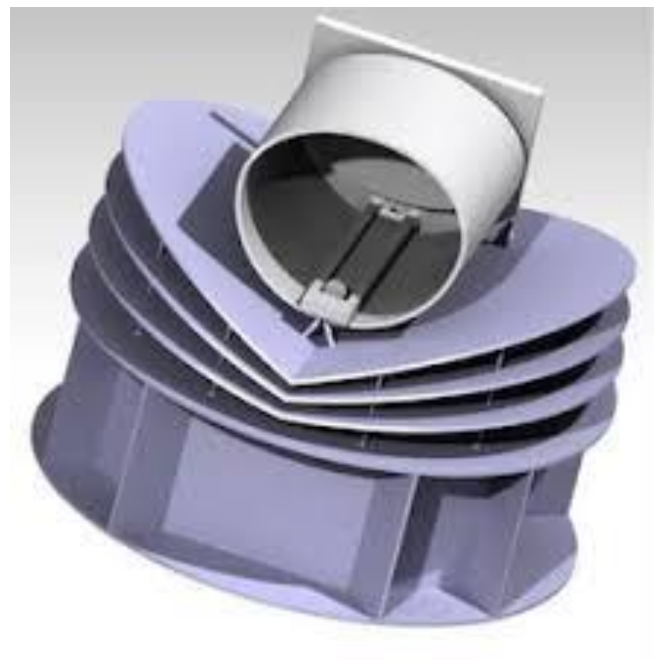
- Orient the solar array toward Sun
- Transfer power from solar array to satellite
- Development effort
  - Mechanical loads during launch
  - Mechanical load in orbit (thrusters)
  - Complex electrical / mechanism interactions
- Qualification effort
  - Specific, bespoke mission development
  - Lifetime demonstration: number of revolutions, in vacuum, under power



Exercice – Sizing ARIEL Solar Panel

- **ARIEL (Atmospheric Remote-sensing Exoplanet Large-survey)** is one of missions selected by the European Space Agency (ESA) for its next medium-class science mission due **for launch in 2026**.
- The goal of the ARIEL mission is to **investigate the atmospheres of several hundreds planets orbiting distant stars** in order to address the fundamental questions on how planetary systems form and evolve.





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Exercice – Sizing ARIEL Solar Panel

- **Hypotheses:**
  - Solar Cell: Azurspace 3G30C
  - Required SA Power: 745 W
  - Solar Flux at L2: 1336 W/m²
  - Maximum Solar Array Angle: 25,5°

  - Loss factor 0.934
  - Harness Vdrop 1.5V
  - Blocking diode Vdrop 0.8V

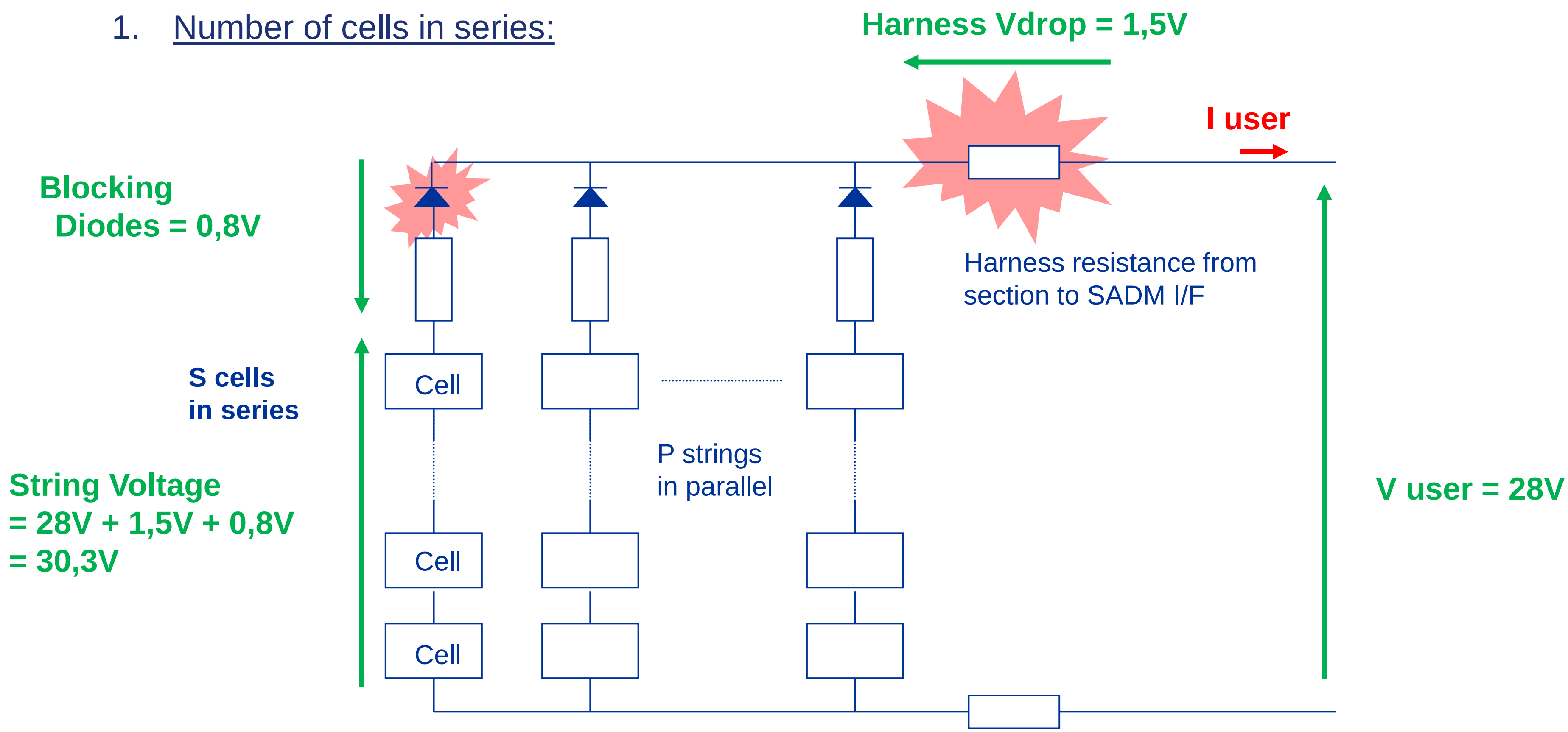
  - Max mission duration 6 years
  - Radiation dose: 5E+14 MeV
  - Temperature range [80°C; 100°C]
    - *Note: size the solar panel for 80°C, which is the nominal temperature in operation. Even if 100°C would be a worst case.*

  - Bus voltage 28V
  - Fill factor 80%

- **Size of the Solar Panel?**

Exercice – Sizing ARIEL Solar Panel - Solution

1. Number of cells in series:



String Voltage = 30,3V

Exercice – Sizing ARIEL Solar Panel - Solution

1. Number of cells in series:
   - We assume that the regulator can operate at the Maximum Power Point.
   - We calculate Vmp for the worst case conditions:
     - Radiation EOL: 5E+14 MeV

Electrical Data

		BOL	2,5E14	5E14	1E15
Average Open Circuit V_{oc}	[mV]	2700	2616	2564	2522
Average Short Circuit I_{sc}	[mA]	520.2	518.5	514.0	501.9
Voltage at max. Power V_{mp}	[mV]	2411	2345	2290	2246
Current at max. Power I_{mp}	[mA]	504.4	503.2	500.6	486.6
Average Efficiency η_{bare} (1367 W/m^2)	[%]	29.5	28.6	27.8	26.5
Average Efficiency η_{bare} (1353 W/m^2)	[%]	29.8	28.9	28.1	26.8

Standard: CASOLBA 2005 (05-20MV1, etc); Spectrum: AMO WRC = 1367 W/m^2; T = 28 °C

     - Vmp = 2,29V (@28°C) – No impact from the flux other than temperature second effect.
     - Temperature: we calculate Vmp @80°C

Temperature Gradients

			BOL	2,5E14	5E14	1E15
Open Circuit Voltage	$\Delta V_{oc}/\Delta T\uparrow$	[mV/°C]	- 6.0	- 6.2	- 6.2	- 6.3
Short Circuit Current	$\Delta I_{sc}/\Delta T\uparrow$	[mA/°C]	0.32	0.35	0.31	0.39
Voltage at max. Power	$\Delta V_{mp}/\Delta T\uparrow$	[mV/°C]	- 6.1	- 6.3	- 6.3	- 6.4
Current at max. Power	$\Delta I_{mp}/\Delta T\uparrow$	[mA/°C]	0.28	0.27	0.20	0.29

     - $\frac{\Delta V_{mp}}{\Delta T} = \frac{x-2290}{80-28} = -6{,}3$ → Vmp =1,96V (@80°C)
     - Number of cells in series: 30,3V / 1,96V = 15,4 → **16 cells**

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Exercice – Sizing ARIEL Solar Panel - Solution

2. Number of strings in parallel:

- We calculate Imp for the worst case conditions (same process than Vmp):

  - Radiation EOL: 5E+14 MeV
  - Imp = 500,6mA (@28°C and AM0 1367W/m²) – Impact from the flux, to be estimated below.

  - Temperature: we calculate Imp @80°C
  - $\frac{\Delta I_{mp}}{\Delta T} = \frac{x-500,6}{80-28}$ =0,2 → Imp =511mA (@80°C and AM0 1367W/m²)

  - Worst case flux received = 1336 W/m² x cos(25,5°) = 1206W/m²

  - Impact on Imp = 511mA x 1206/1367 = 450,8mA

  - Loss factor: 450,8mA x 0,934 = 421mA

  - Current required: 745W / 28V = 26,6A

  - Number of strings in parallel: 26,6A / 0,421A = 63,2 → **64 strings**

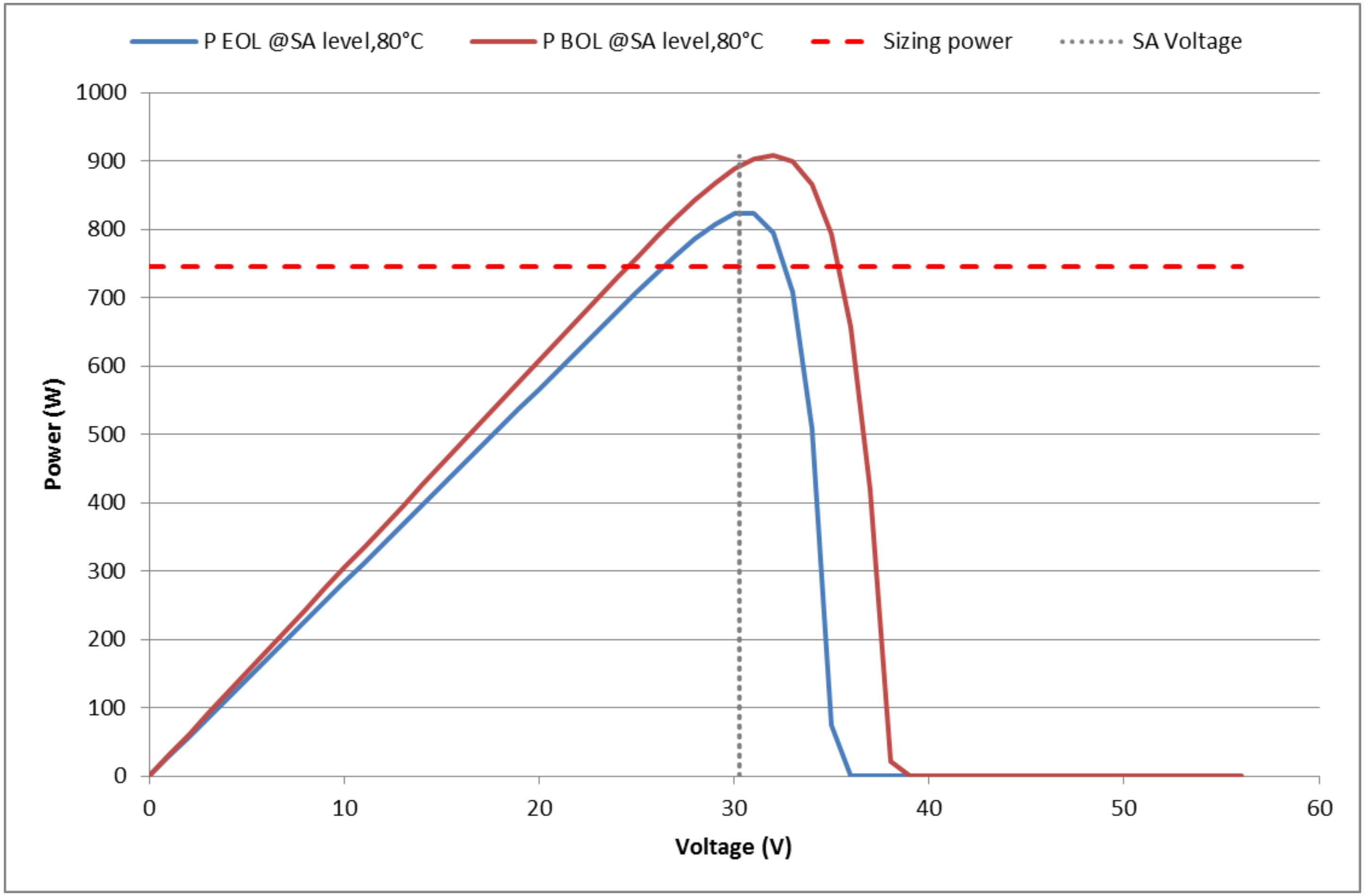
Exercice – Sizing ARIEL Solar Panel - Solution

3. Size of the Solar Panel

- Solar panel configuration: 16S 64P
- Active surface: 16 x 64 x 30,18 cm^2 = 3,1 m^2
- Cells surface: 16 x 64 x 32 cm^2 = 3,28 m^2
  - *Note: active surface is slightly different from the total active surface (Dimmensions of the cell are 8 x 4cm)*
- Mechanical surface: 3,28 / 0,8 = 4,1 m^2
- Estimated mass (cells) = 6,55 kg

Exercice – Sizing ARIEL Solar Panel - Solution

4. ARIEL P-V curve



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SUMMARY

Summary

- **Power generation design and sizing is highly dependent of the mission, the spacecraft power needs and of the space constraints linked to the orbit**

- **Power generation in spacecraft is mainly ensured by photovoltaics means, which represent a major mass / cost contributor to the mission with many systems interactions**

- **Overall power system optimisation is required to get the optimum system and cost performances**

Questions