ELECTRICAL POWER SYSTEMS

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THALES ALENIA SPACE

IN BELGIUM

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OVERVIEW

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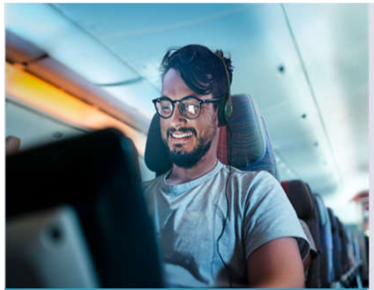
THALES: HELPING OUR CUSTOMERS MASTER EVERY DECISIVE MOMENT



Aerospace

Make flying safer, easier and more efficient

Space

Optimise the use of our planet's and solar system's resources

Ground transport

Connect journeys to move people and goods safely and efficiently

Defence

Protect citizens and make the world safer

Digital Identity and Security

Protect states, cities & critical infrastructures

80,000 collaborators

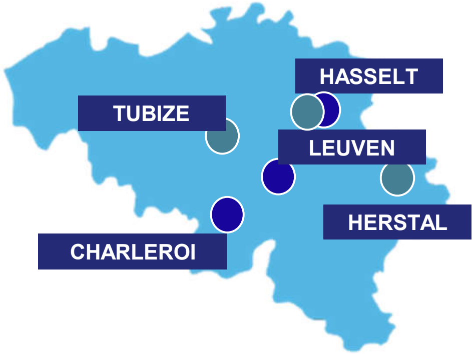
MORE THAN **68** countries

1 bn €
Self-funded R&D*
* Does not include externally financed R&D

Sales in 2018
€19 billion

50 % Defence
Civil

THALES IN BELGIUM: AN INVESTMENT OF MORE THAN 50 YEARS



2 entities

6 sites

1,000 collaborators

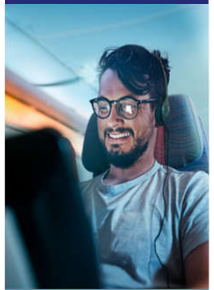
SPACE

Charleroi
Leuven
Hasselt

Power and distribution systems for launch vehicles and satellites

Automated factory for assembly of photovoltaic cells

AEROSPACE



Tubize
Hasselt

Digitisation of processes linked to air-based operations, based on EFB solutions

TRANSPORT

Tubize

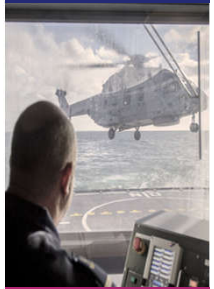
Ground transport systems

DIGITAL IDENTITY & SECURITY

Tubize

Secure communication and information systems

DEFENCE & SECURITY



Tubize
Herstal

Secure communication and information systems

Air/Ground rocket systems

SPACE FOR LIFE

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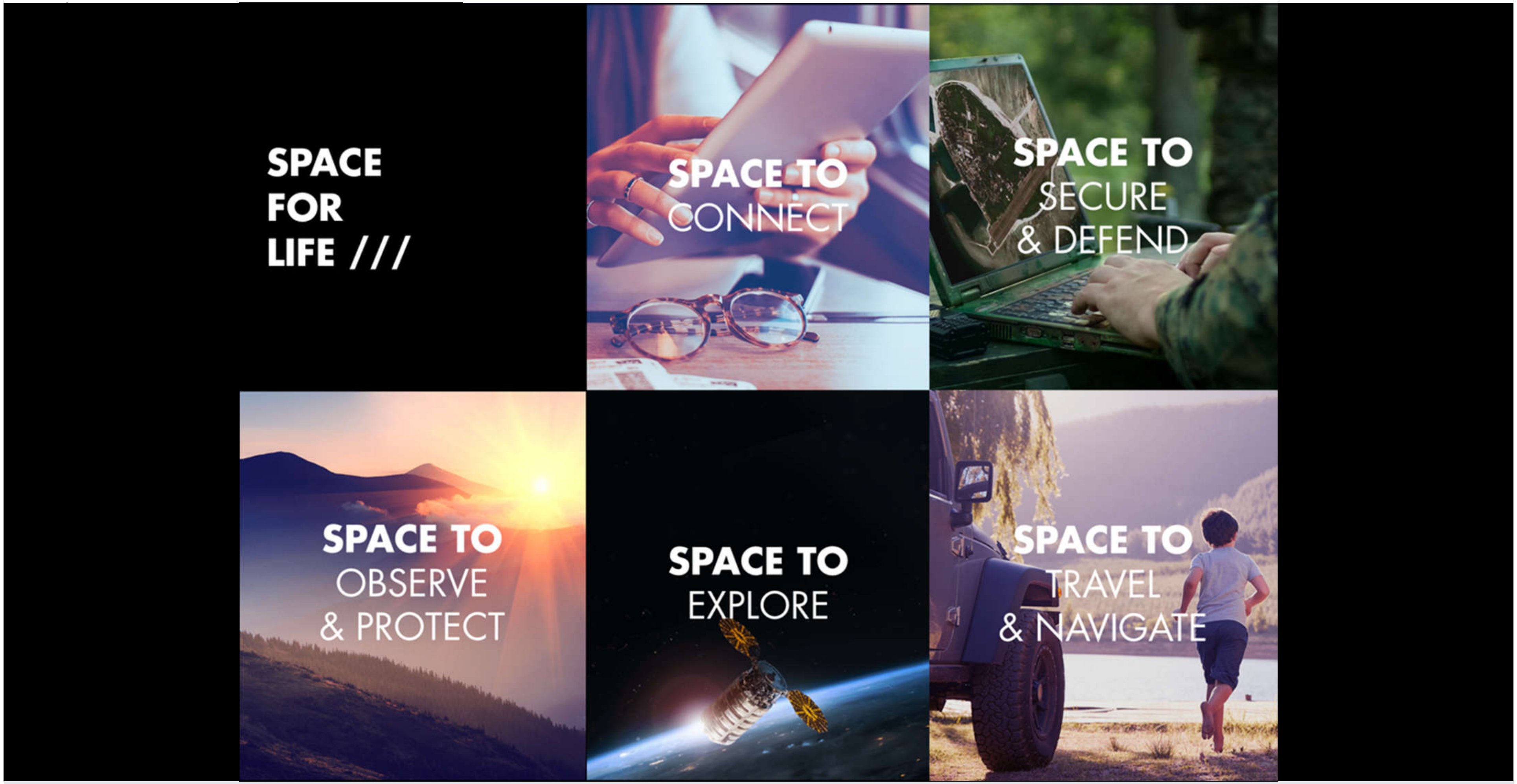
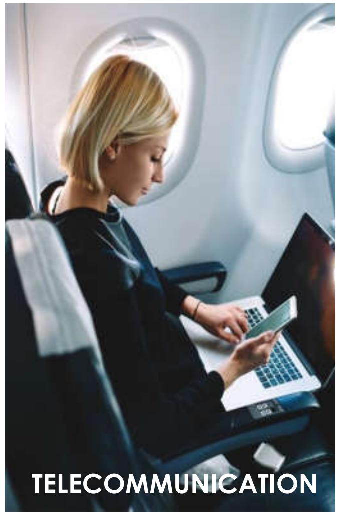

SPACE FOR LIFE ///
SPACE TO CONNECT
SPACE TO SECURE & DEFEND
SPACE TO OBSERVE & PROTECT
SPACE TO EXPLORE
SPACE TO TRAVEL & NAVIGATE

THALES ALENIA SPACE: OPTIMISING THE USE OF OUR PLANET'S AND OUR SOLAR SYSTEM'S RESOURCES



Fixed/Mobile

Broadband

Dual/Military

Secured lines

Climate change

Meteorology

Oceanography

Intelligence Surveillance

Planetary science

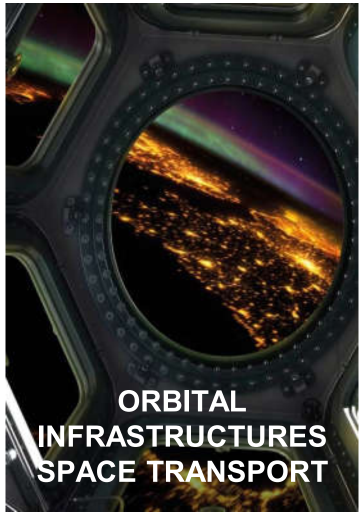
Fundamental physics

Astronomy

Localisation

Aeronautical communications

Data collection



Human spaceflight

Space transport systems

International Space Station

An end-to-end offer from equipment to space systems

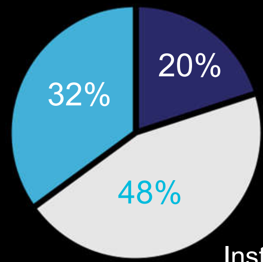
KEY FIGURES

JOINT VENTURE

THALES (67%)
LEONARDO (33%)

MORE THAN 8,000 EMPLOYEES

BREAKDOWN BY MARKET



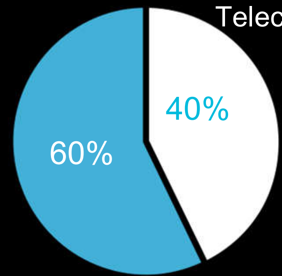
REVENUE

€2.5 billion

IN 2018

17 SITES WORLDWIDE

BREAKDOWN BY ACTIVITY



A SELECTION OF CUSTOMERS

AROUND THE WORLD

SCIENCE & EXPLORATION
ASI - CNES - ESA - ESTEC - NASA - ROSCOSMOS - UK SPACE AGENCY

OBSERVATION, METEOROLOGY & ENVIRONMENTAL MONITORING
CNES - ESTEC - EUMETSAT - ESA - EUROPEAN UNION - FRENCH GOVERNMENT - ITALIAN GOVERNMENT - NPO LAVOTCHKIN - SOUTH KOREA - EUROPEAN COMMISSION

TELECOM OPERATORS
ARABSAT - AVANTI COMMUNICATIONS - EUTELSAT - HISPASAT - INDOSAT INDONESIA - INMARSAT - ISS-RESHETNEV - KT - BANGLADESH MINISTRY OF INFORMATION - TURKMENISTAN MINISTRY OF COMMUNICATIONS - PT TELKOM INDONESIA - RSCC - SES GLOBAL - TELEBRAS - YAHSAT

SATELLITE CONSTELLATION OPERATORS
GLOBALSTAR - IRIDIUM - LEOSAT - O3B - TELESAT CANADA

MILITARY TELECOMMUNICATION SATELLITES
BRASIL - FRANCE - GERMANY - ITALY - KOREA

NAVIGATION
CLS - EUROPEAN GNSS AGENCY - ESA - EUROPEAN UNION - KARI

SATELLITE INTEGRATORS
AIRBUS DEFENSE & SPACE - BALL AEROSPACE & TECHNOLOGIES - MAXAR MITSUBISHI

THALES ALENIA SPACE

IN BELGIUM

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THALES ALENIA SPACE IN BELGIUM

A global leader in power electronics for satellites and launch vehicles

3 sites

Charleroi
Leuven
Hasselt

A Belgian leader in the space sector

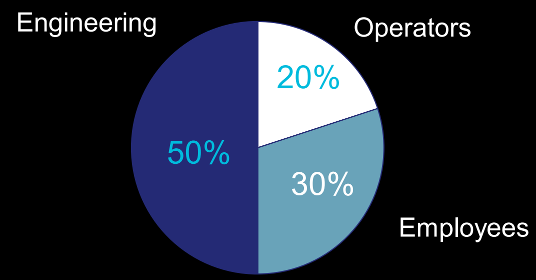
56 years of experience

KEY FIGURES

3 SITES

Charleroi,
Leuven & Hasselt

MORE THAN
630 COLLABORATORS



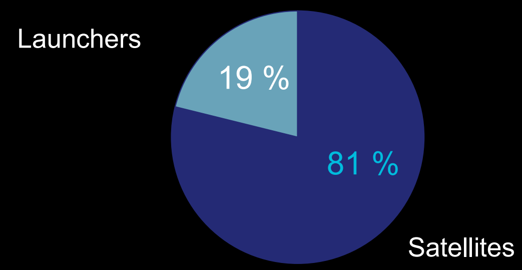
Revenue

Revenues stable around 100 M€ over the past three years

% OF OUR REVENUE INVESTED IN R&D

~ 20 %

BREAKDOWN
BY ACTIVITY



THALES ALENIA SPACE IN BELGIUM

/// A wide range of products dedicated to Thales Alenia Space and our clients around the world

PRODUCTS FOR

PLATFORM ELECTRONICS

PCU - PCDU

Strong heritage (~ 200 FMs) for all types of Power Conditioning and Distribution Units

PPU

A European leader in power supplies for electrical propulsion (> 70 FM's)

Avionics

New generations of avionics for GEO (SDIU) and LEO/MEO (RTU) applications

PAYLOAD ELECTRONICS

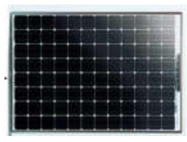
TWTA

Annual production: 200 Travelling Wave Tube Amplifiers

DC/DC

Annual production: > 150 units

SOLAR PANELS



PVA

Automated production of Photovoltaic Assemblies using a 4.0 approach

LAUNCH VEHICLES

POWER SUPPLIES

The leading supplier of electronics for European launchers: Ariane, Soyuz and Vega

New Space : We are preparing the future

with the development of the next generation of equipment already initiated

SATELLITE PRODUCTS: PLATFORM ELECTRONICS

A global leader in electrical power supply sub-systems for satellites

PCU (Power Conditioning Unit)
Regulates and conditions the electrical energy supplied by the solar panels and the batteries (GEO)

PCDU (Power Conditioning & Distribution Unit)
In addition to power conditioning they also provide distribution functions for the constellations (MEO-LEO)

European leader in Power Supply for Electrical Propulsion

PPU (Power Processing Unit)

PPU MK2
Power supply and thruster control for satellite station keeping

PPU MK3
Also performs orbit rising and re-entry from orbit

TODAY

Avionics: Disruptive technology

SDIU (Standard Distribution & Interface Unit)
Distribution and Avionics interfaces for GEO satellites

RTU (Remote Terminal Unit)
Distribution and Avionics interfaces for LEO and MEO satellites

TOMORROW

New Space:

We are developing high-performance integrated electronics for the next-generation of satellite platforms

LEO, MEO, GEO & Constellations

SATELLITE PRODUCTS: PLATFORM ELECTRONICS

Just some of our success stories

Copernicus: We are a major player in the European Copernicus programme, dedicated to environmental surveillance >

> On-board PCDU

Iridium® NEXT, the most sophisticated telecommunications system in history >

> 81 PCDU ordered

Thales Alenia Space in Belgium
A global reference for the constellation market

Neosat, the next generation of European telecommunications satellite platforms in geostationary orbit >

> PCDU, SDIU, PPU ordered by Thales Alenia Space (Spacebus Neo) and Airbus (Eurostar). *These equipment are also on board the OHB (Electra) satellites*

Galileo is the European Union's programme for developing a global radio-navigation system. It is employed for sea, air and land transport, relief operations, public works, agriculture and more. >

> 30 PCDU ordered

ExoMars 2020 will perform drilling to a record depth of 2 metres beneath the surface of Mars and subsequently analyse the samples in its highly sophisticated mini-laboratory >

> 1 PCDU and 1 RTU delivered

SATELLITE PRODUCTS: PAYLOAD ELECTRONICS

TODAY

A reference in electrical power supply for travelling wave tube amplifiers

400 channels per year

TWTA (Traveling Wave Tube Amplifier):
These emitters amplify, via travelling wave tubes, the signals transmitted to Earth by satellites for TV, radio, Internet and other telecommunication applications

Available in "Single", "Dual" and "Flexible" versions

A specialist in DC/DC converters

LPLC (Low Power Low Cost)
Highly flexible hybrid power supply and DC/DC converter

PSU (Power Supply Unit)
Pulsed power supply for radars and altimeters

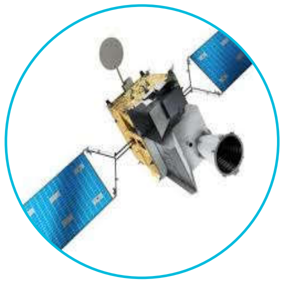
TOMORROW

New Space:
Development of the next generation of equipment **using an "Component-Off-The-Shelf" approach**

SATELLITE PRODUCTS: PAYLOAD ELECTRONICS

Just some of our success stories

Konnect VHTS is the most powerful telecommunication satellite in the world. VHTS digital payload + Spacebus Neo platform: a winning combination! >
> 61 TWTA on board



MTG: Meteorology in Europe is becoming increasingly accurate: from an image every 30 minutes in the 1980s to one every 15 minutes today and, soon, a refreshed image every 10 minutes, thanks to MTG satellites >
> 18 TWTA and 43 LPLC ordered

Pleiades & CSO: 30 years of surveillance. Thales Alenia Space is the exclusive supplier of Ultra-High Resolution optical instruments for French intelligence satellites >
> TWTA, PSU and LPLC on board

SWOT, the oceanography satellite from French (CNES) and American (NASA) space agencies >
>TWTA, LPLC and DC/DC on board

New Horizons: The New Horizons mission is the first of Nasa's New Frontiers planetary exploration programme to reach the edge of the solar system >
>TWTA on board

SATELLITE PRODUCTS: SOLAR PANELS

/// The only company in Europe to have an automated factory for assembling photovoltaic cells

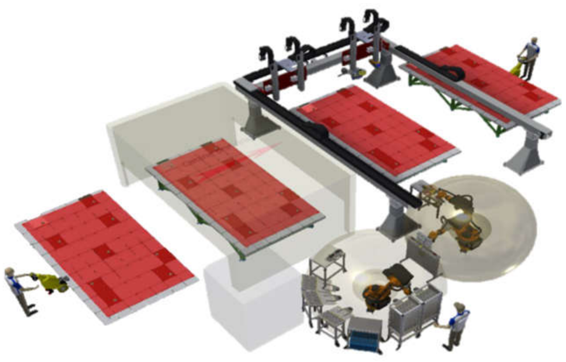
PVA (PHOTOVOLTAIC ASSEMBLIES)
relies on the skills of the Thales Alenia Space teams in Cannes for creating solar generators

OBJECTIVES

/// Reduce costs by adopting a disruptive approach (automated line) to meet the needs of the market

/// Reduce the supply chain

/// Access the constellation market



INDUSTRY 4.0

Robotic assembly of the panel

Digital management of data and traceability

In-line testing and checks

Introduction of augmented reality

Swift and significant analysis of smart data from all sources

LAUNCHER PRODUCTS

A leader in on-board electronics on Ariane 5

The main supplier for Ariane 5

Development and production of control and command units for the launcher

23 equipment and modules per launcher

6 to 7 launches per year

The only non-Russian supplier on Soyuz (French Guyana)

Exclusive supplier of the Soyuz safeguard chain (Kourou)

PRS (Passive Repeater System)
allows communication between the on-board payloads and the ground control systems before launch

TODAY

The adventure continues with Ariane 6

Development of the safeguard system

Development of the electronics for the actuators system of the nozzles

The prices of the equipment have been halved, thanks to the New Space approach

TOMORROW

Towards intelligent on-board safeguards that simplify operations

A redesign of electronics and design for reusable stages (CALLISTO)

A stronger integration of the electronics

An electrification of the motors on the launchers

Expansion into the field of high-altitude vehicles (balloons, drones, etc.)

LAUNCHER PRODUCTS

Just some of our success stories

Thales Alenia Space has been a pioneer and contributor to the European launcher industry for more than 40 years!

On board every European launcher

Delivery of the majority of the test benches for the Ariane family (Ariane 1 through 5)

A POWERFUL AND EFFICIENT INDUSTRIAL BASE

A LEAN CULTURE

A continuous and long-lasting improvement

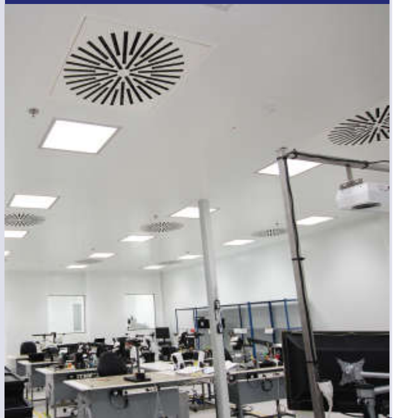
INDUSTRY 4.0

To consolidate our future

COMPLETE SUPPLY CHAIN

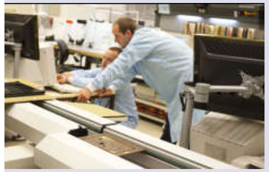
Hybrids, Magnetics, Assembled Printed Circuit Boards, Integration and Tests

CLEAN ROOMS



> 7,850 m^2

A COLLECTION OF HIGH-QUALITY PRODUCTION AND TEST MEANS



OUR ATTRACTIVENESS AS AN EMPLOYER

We are hunting for solutions to the constantly-changing challenges of telecom, space, navigation, Earth observation, defense and science – and **it is the thrill of that hunt that allows us to attract the best people.**

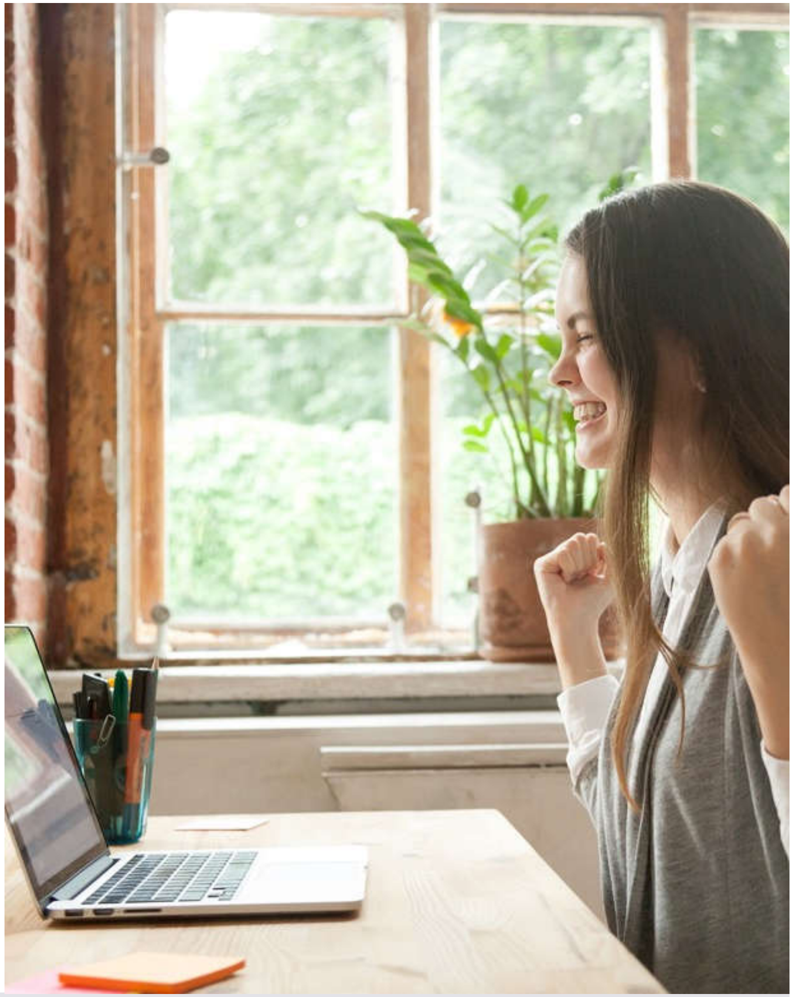
Career development

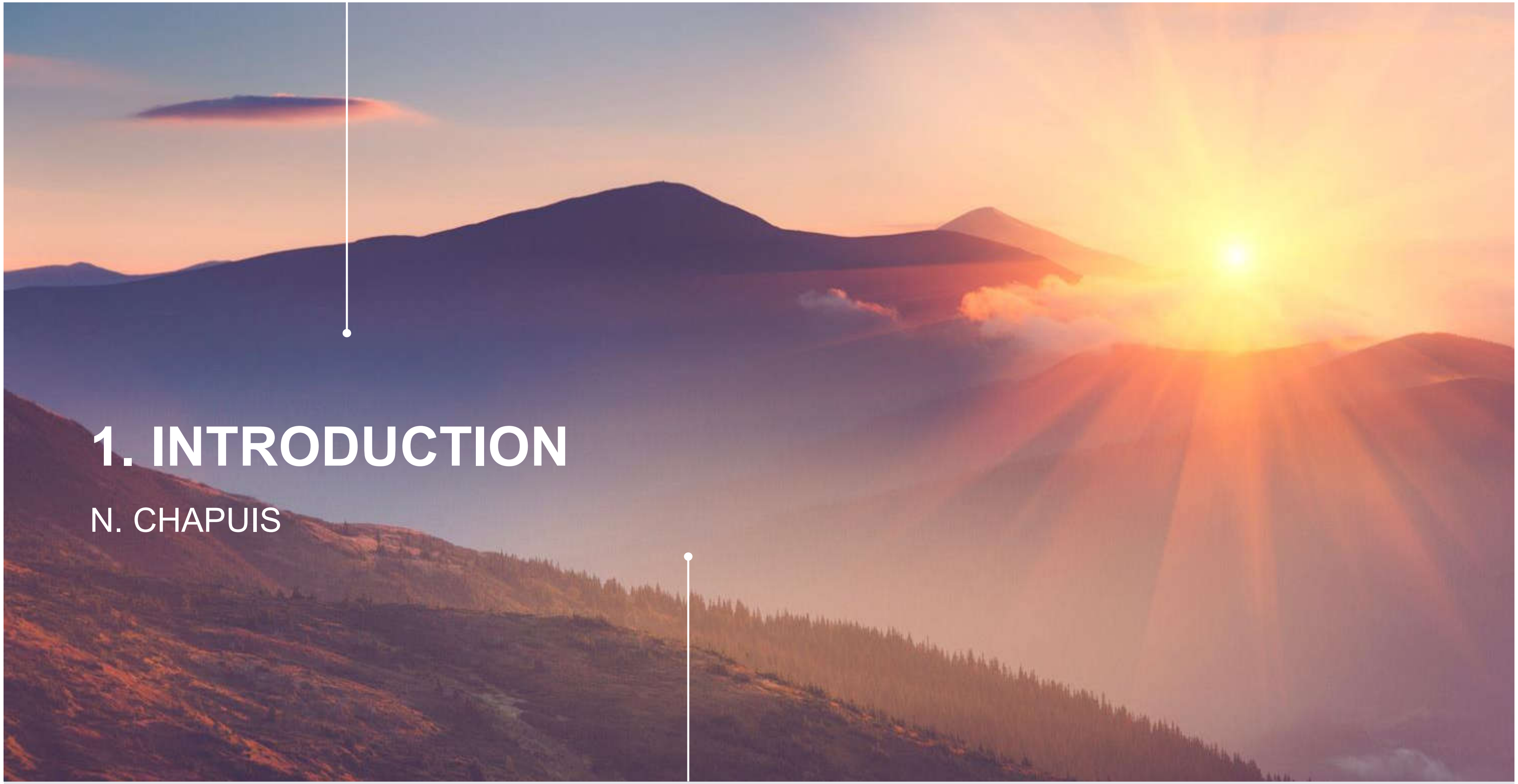
- Opportunity to work towards different roles whether technical, managerial or even in production and support roles (purchasing, logistics, supply chain…)
- Internal training (training, on-the-job training, participation in various seminars, etc.) to achieve your objectives

Diversity

Mobility

Go to www.thalesgroup.com/careers





1. INTRODUCTION

N. CHAPUIS

INTRODUCTION

///Training

- **ELECTRICAL / ELECTRONIC ENGINEER FROM ECAM-BRUSSELS (2004)**

///Professional career in TAS-Belgium

- **ELECTRONIC DESIGNER**
  - /// PCDU GlobalStar-2 constellation
  - /// PCU ArSat
- **TECHNICAL MANAGER**
  - /// PCDU O3b constellation
  - /// Military classified PCDU for CNES
  - /// C-PCDU Exomars 2020
- **PCDU/PCU/PPU ENGINEERING TEAM LEADER**

INTRODUCTION / EPS GENERAL INFORMATION

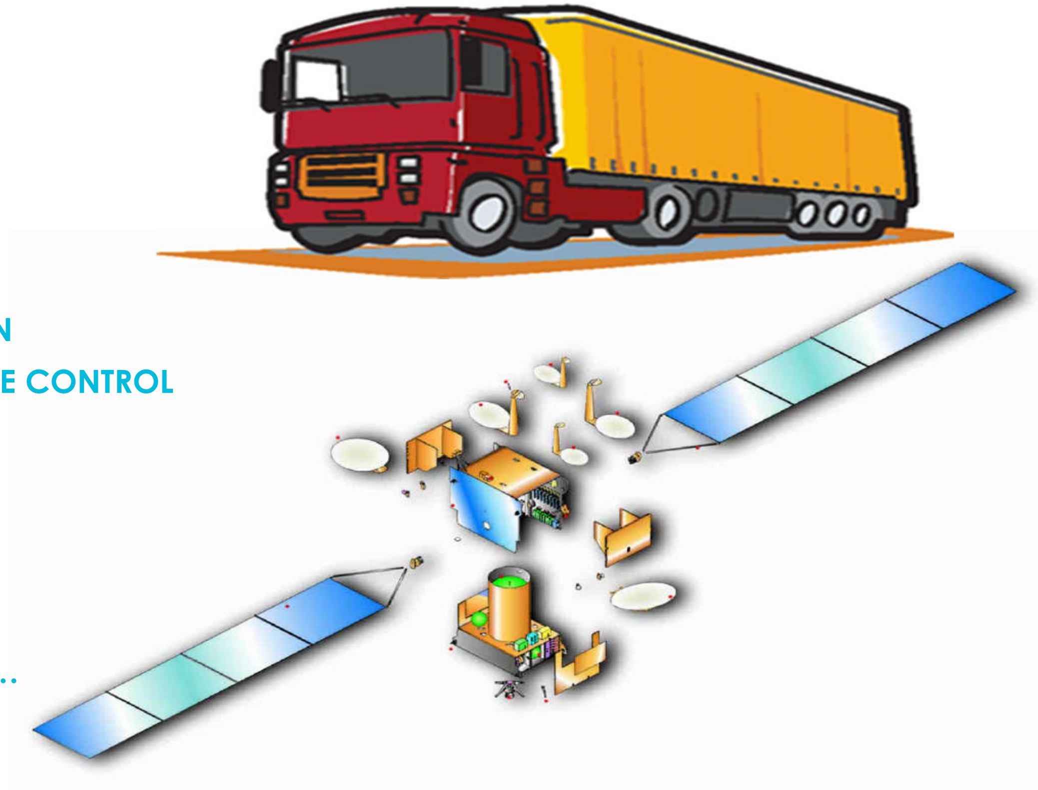
///A satellite is made of…

/// P/F (Platform)

- **MECHANICAL & THERMAL STRUCTURE**
- **ELECTRICAL SYSTEM, AVIONIC, PROPULSION**
- **ON-BOARD COMPUTER, SOFTWARE, REMOTE CONTROL**
- **ENERGY SOURCES: SOLAR, BATTERIES, FUEL**

/// P/L (Payload)

- **ANTENNAS, TWTA, …**
- **CAMERA, ALTIMETER, RADAR, DETECTORS, …**
- **CLOCK, SCIENTIFIC INSTRUMENTS,…**



INTRODUCTION / EPS GENERAL INFORMATION

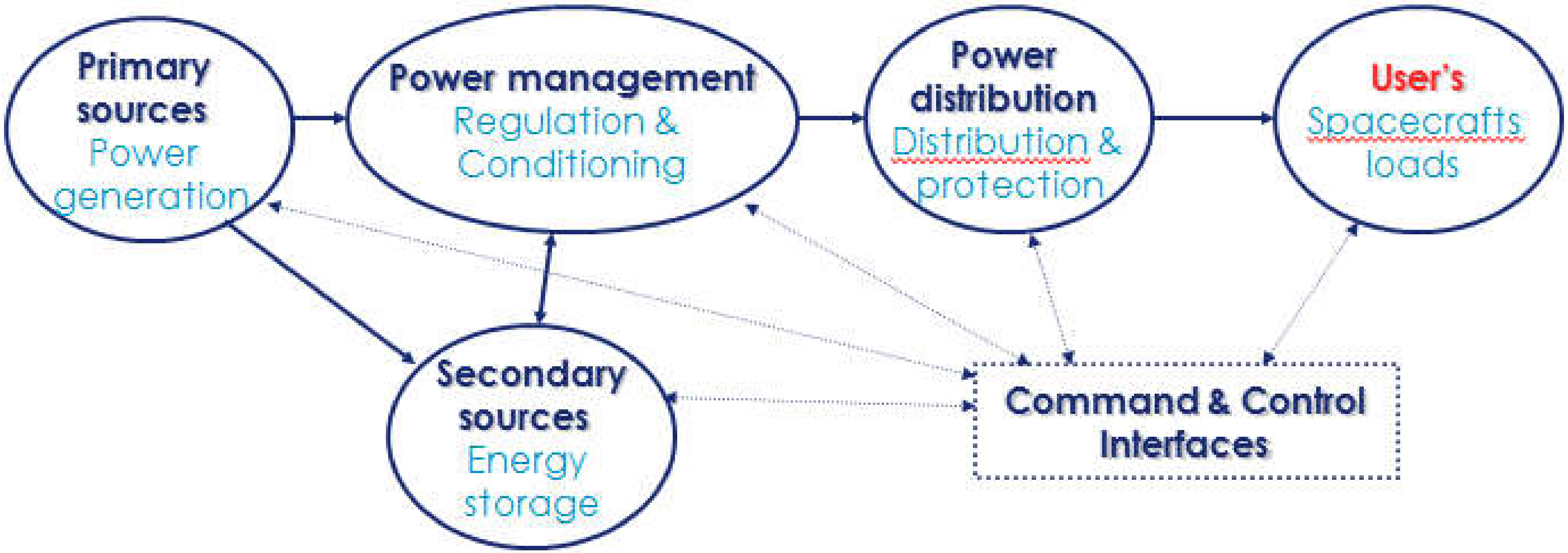
/// Satellite Electrical Power Subsystem (EPS) shall

- **PROVIDE TO EACH S/C PLATFORM AND PAYLOAD EQUIPMENT THE REQUIRED POWER OVER THE WHOLE MISSION**
- **HAVE ENERGY CAPACITY TO POWER EQUIPMENTS IN CASE OF ORBITAL NIGHT PHASES, TRANSIENT PHASES AND PEAK POWER DEMAND**
- **AUTONOMOUSLY MANAGE THE AVAILABLE POWER IN ORDER TO PROVIDE THE EQUIPMENT'S POWER AND TO CHARGE THE BATTERY**
- **FULFILL SOME DISTRIBUTION REQUIREMENTS PROVIDING ON/OFF PROTECTED POWER LINES, HEATER SUPPLY (FOR S/C THERMAL CONTROL NEEDS) AND COMMANDING PYRO LINES (E.G. SA AND ANTENNA DEPLOYMENT)**

<u>NOTE:</u> POWER SYSTEM FAILURE MEANS THE LOSS OF MISSION

INTRODUCTION / EPS GENERAL INFORMATION

/// General functional block diagram



INTRODUCTION / EPS GENERAL INFORMATION

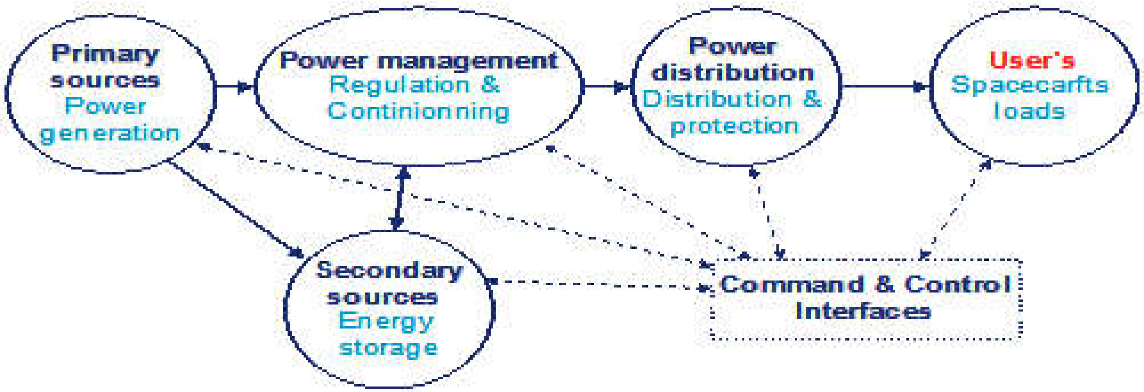
/// Functions (1)

/ POWER GENERATION

- The power is generated from different sources ('fuel') or combination of them: the Solar radiant energy (solar cells via photovoltaic effect), Chemical (piles – fuel cells), nuclear (RTG), mechanical (reaction wheels), …
- Primary sources convert 'fuel' into electrical power

/ ENERGY STORAGE

- The energy is generally stored under an electro-mechanical form and retrieved under an electrical form
- The storage of the energy is done by a secondary source, when the primary system's energy is not available or insufficient



INTRODUCTION / EPS GENERAL INFORMATION

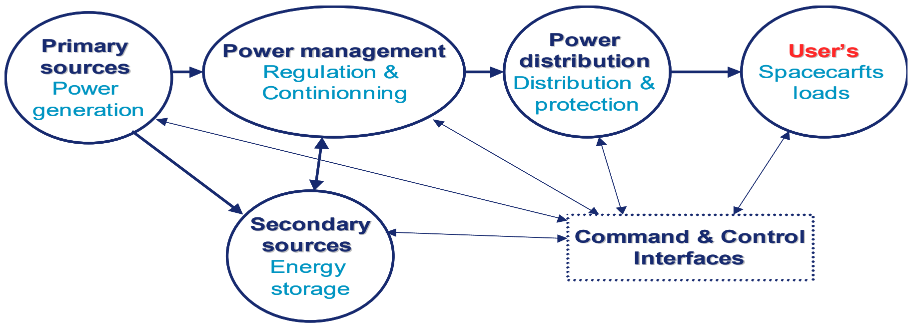
/// Functions (2)

/ CONDITIONING AND REGULATION

- This function covers everything which is required to adapt the primary sources to the need of users 'equipment'
- Regulators
  - To maintain a constant voltage or current
  - Regulation of battery charge and discharge, regulation of the commutation of solar generator sections

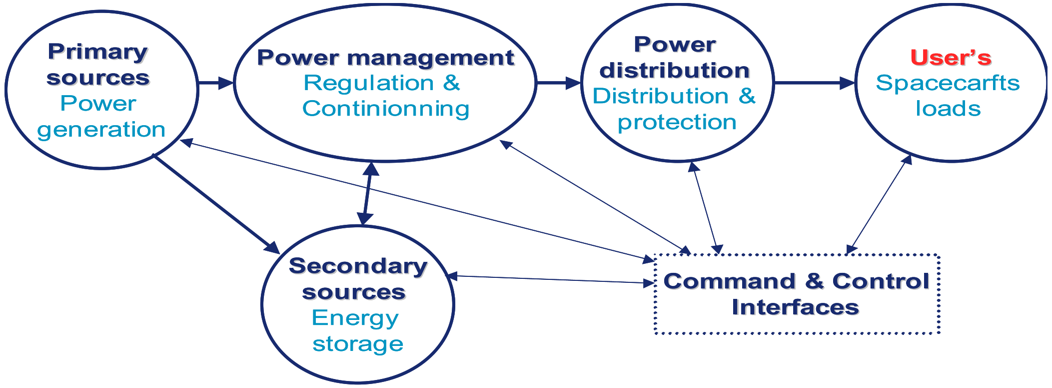
/ DISTRIBUTION

- To distribute the conditioned power to users
- DC/DC voltage converters
- ON/OFF switches
- Does not include the harness



INTRODUCTION / EPS GENERAL INFORMATION

/// Functions (3)



PROTECTION

- To avoid a propagation of failures or any Single Point Failure
- Protections against short-circuits
  - Fuses
  - Circuit breakers

CONTROL

- Observing parameters
  - Current, voltages, temperatures, status, …
- Information are transmitted to the Ground by telemetry for mid-term and long-term monitoring
- Information are transmitted to the On-Board Computer for real-time monitoring

COMMAND

- Configuration setting (nominal, safety, recovery, …)
- Parameters
- ON/OFF

INTRODUCTION / EPS GENERAL INFORMATION
SYSTEM DRIVERS / SYNTHESIS

/// The orbit

- **LOW EARTH ORBIT (LEO), GEOSTATIONARY (GEO), MEAN EARTH ORBIT (MEO), SUN SYNCHRONOUS ORBIT (SSO), SUN CENTRIC (INTERPLANETARY), …**

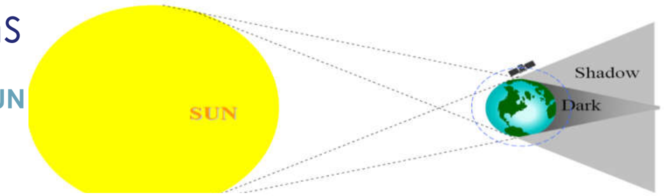
/// The mission

- **(Life) duration**
- **Energy budget**
  - Mission profiles
  - Payload needs
  - Max and Mean power
  - Orientation (attitude) of the satellite
- **Reliability requirements**

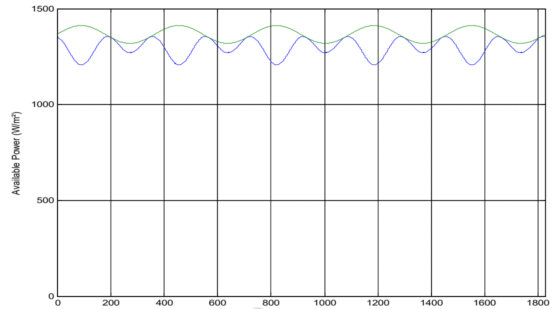
INTRODUCTION / EPS GENERAL INFORMATION
SYSTEM DRIVERS / ORBITS

///LEO (Low Earth Orbit) / Scientific applications

Ø SUN

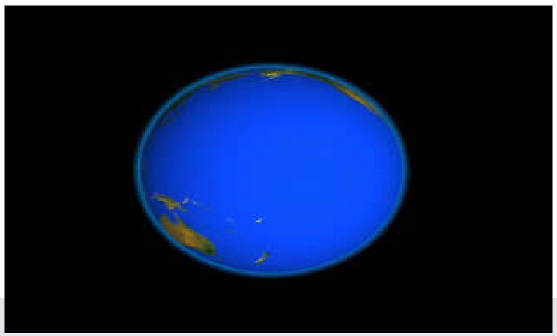


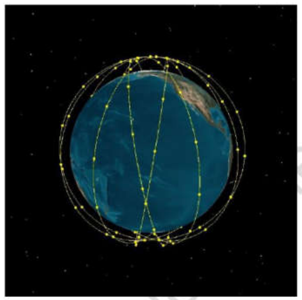
- **ORBIT**
  - Altitude: between 350 and 1000 km
  - Duration:~2 hours
  - Low sensitivity to radiations
- **ECLIPSES**
  - High variability versus the orbit selection
  - Up to 40 % of eclipse duration
  - Thousands of cycles along mission duration



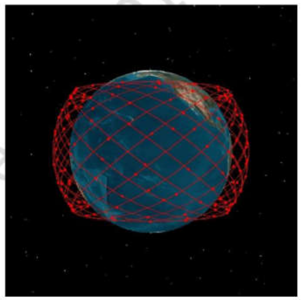
SA flux (sun-synchronous orbit)
- > Min SA flux = 1220 W

SA flux (polar orbit)
- > Min SA flux = 520 W

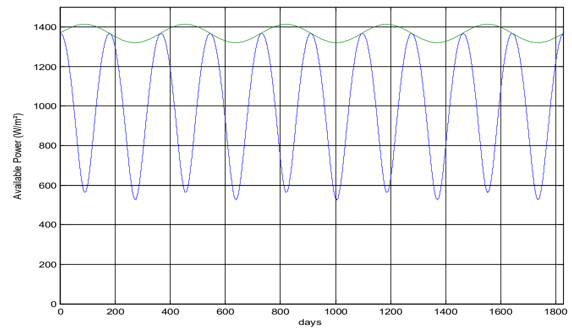




Polar Orbit



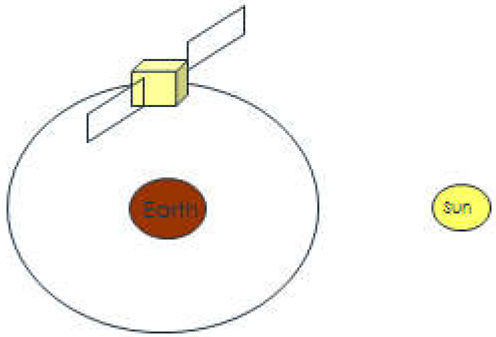
Inclined Orbit



INTRODUCTION / EPS GENERAL INFORMATION

SYSTEM DRIVERS / ORBITS

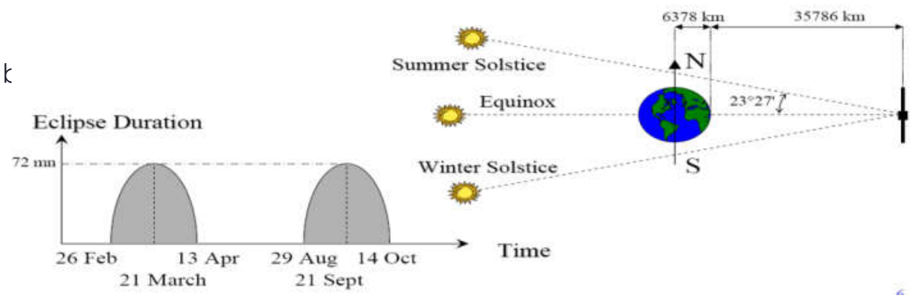
///GEO (Geostationary Orbit): Telecom application



- **ORBIT**
  - Type: Circular
  - Altitude: 35786 km
  - Duration: 24 hours
  - Medium sensitivity to radiations
- **ECLIPSES**
  - Less thqn 1% of mission duration
  - Only during equinoctial periods
  - From few to 72 minutes max

… DURING LIFETIME … BUT UP TO 6 MONTHS ELECTRICAL ORBIT RAISING WITH ELECTRICAL PROPULSION DRASTICALLY MODIFY THE SITUATION

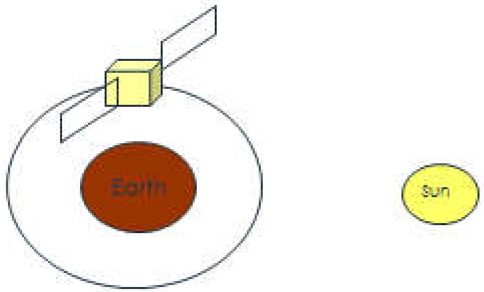
- Increased number of longer eclipses
  - Thermal cycling more severe
  - Ratio charge / discharge impacted
  - Higher battery DoD (especially if thrust has to k
- More stringent radiative environment



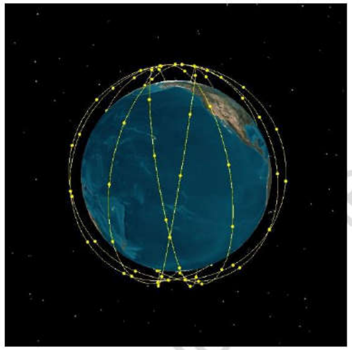
- **MISSION DURATION**
  - 15 years
- **EXAMPLE(S): SPACEBUS BASED SATELLITES, …**

INTRODUCTION / EPS GENERAL INFORMATION
SYSTEM DRIVERS / ORBITS

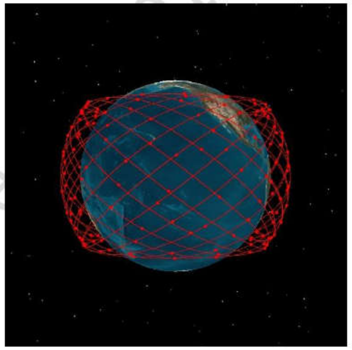
///MEO (Medium Earth Orbit): GPS / TELECOM applications



- **ORBIT**
  - Type: Circular
  - Altitude: 1000 to 20000 km
  - Duration: 12 hours
  - Medium to high sensitivity to radiations (according to orbit height)
- **ECLIPSES**
  - Duration: up to 1 hour
- **MISSION DURATION**
  - Up to 15 years
- **EXAMPLE(S): GLOBALSTAR, GALILEO, IRIDIUM, …**



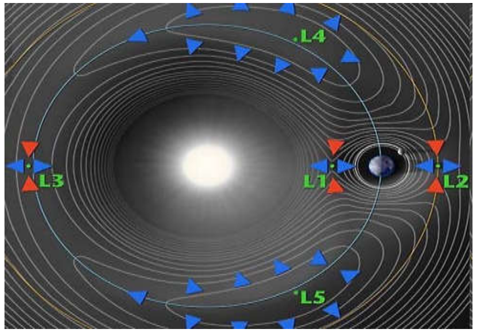
Polar Orbit



Inclined Orbit

INTRODUCTION / EPS GENERAL INFORMATION
SYSTEM DRIVERS / ORBITS

/// Lagrange Point: Scientific applications - ESA



- **POINTS WHERE THE COMBINED GRAVITATIONAL PULL OF TWO LARGE MASSES PRECISELY COMPENSATE THE CENTRIPETAL FORCE REQUIRED TO ROTATE WITH THEM (ANALOGY WITH THE GEOSTATIONARY ORBIT)**
  - Distance from earth for L1,L2: 1.5*10^6 km
- **ECLIPSES**
  - None
- **MISSION DURATION**
  - 3 years
- **EXAMPLE(S): HERSCHEL (L2), PLANCK(L2), GAIA(L2),…**

/// Interplanetary

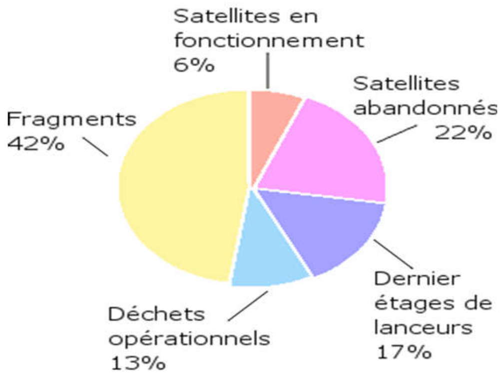
- **CHALLENGE : MANAGEMENT OF SOLAR FLUX, WHICH DECREASES WITH THE SQUARE OF THE DISTANCE TO THE SUN**

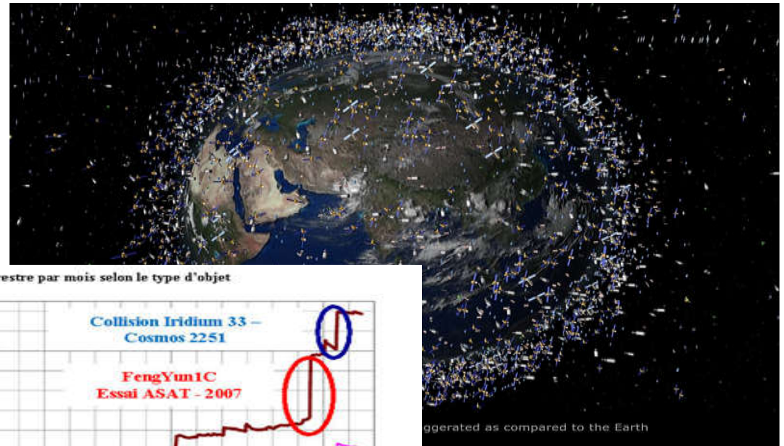
	Distance (AU)	Solar flux (W/m^2)
Mercury	0.39	$9.3\ 10^3$
Earth	1.0	$1.36\ 10^3$
Mars	1.5	582
Jupiter	5.2	48.7
Saturn	9.5	13.5

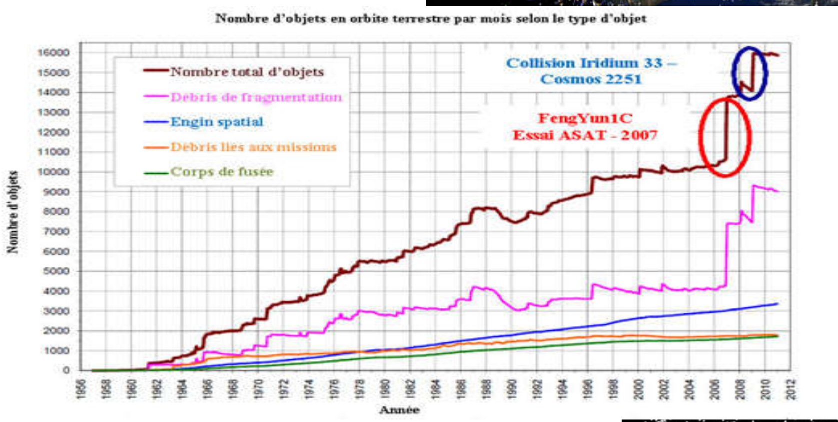
INTRODUCTION / EPS GENERAL INFORMATION
SYSTEM DRIVERS / ORBITS

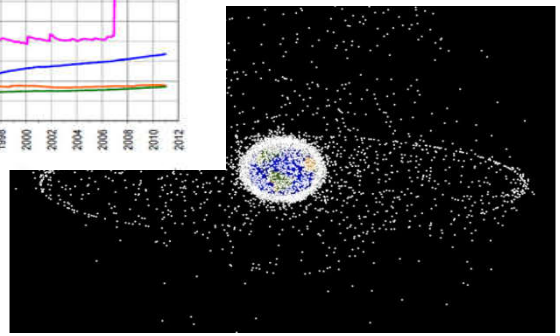
///System drivers / Orbits

M-METEORITE & DEBRIS









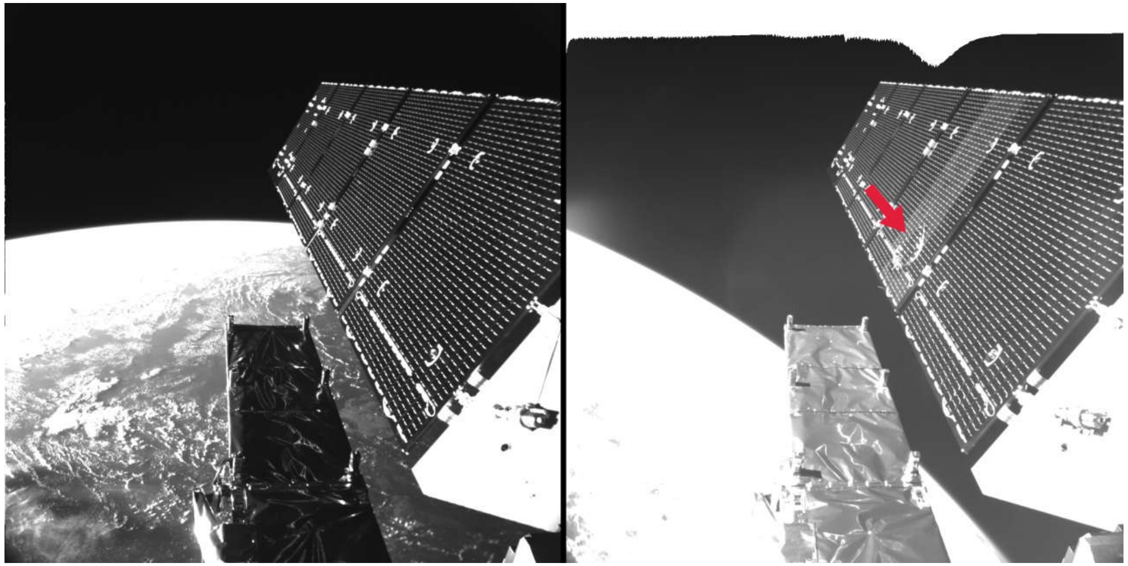
- 15 000 parts > 10cm
- 300 000 parts < 10 cm
- Large concentration between 700 & 1000 km

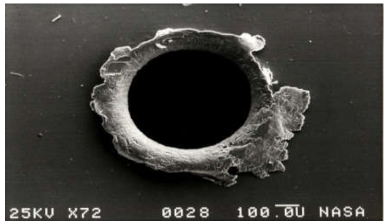
INTRODUCTION / EPS GENERAL INFORMATION

///System drivers / Orbits

LOS (FRENCH RULE) TO AVOID GENERATION OF NEW DEBRIS

- Controlled de-orbitation or
- Parking in specific orbit with complete (propulsion and electronic) passivation (25 years in LEO, 100 years in GEO)



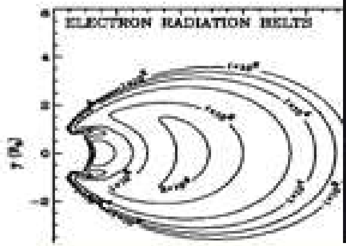


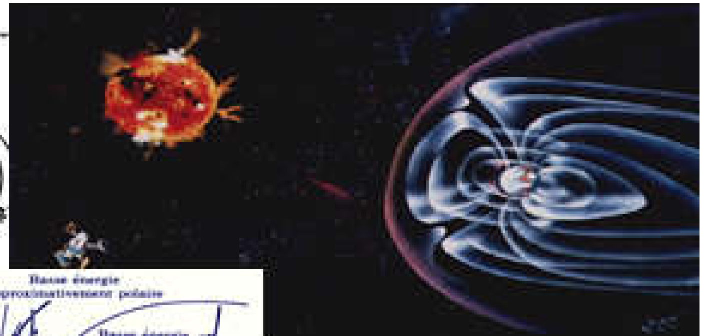
INTRODUCTION / EPS GENERAL INFORMATION

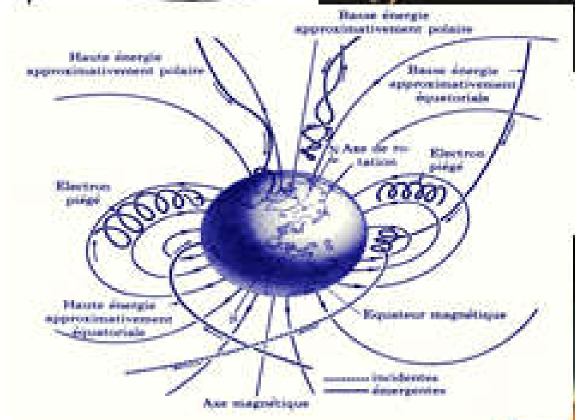
///System drivers / Orbits

/ RADIATION SOURCES

- Trapped electrons
  Van Allen belts
- Trapped protons
  Van Allen belts
- Sun protons
  Sun eruptions
- Space heavy ions
  Cosmic rays





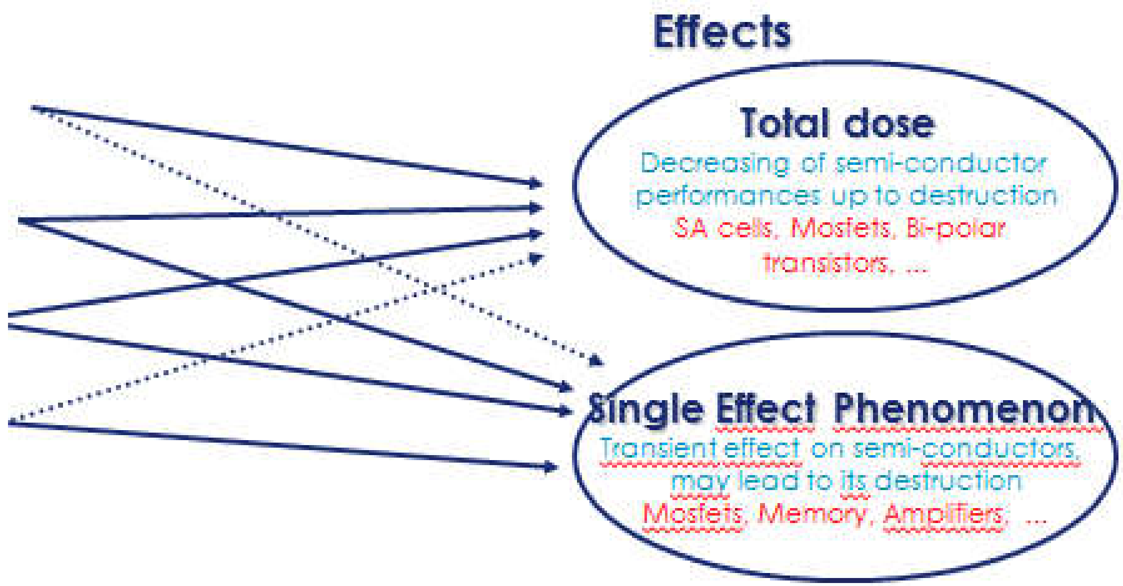


INTRODUCTION / EPS GENERAL INFORMATION

/// System drivers / Orbits

/ RADIATION SOURCES

- Trapped electrons
  Van Allen belts
- Trapped protons
  Van Allen belts
- Sun protons
  Sun eruptions
- Space heavy ions
  Cosmic rays



-> The radiation environment has a direct impact on the definition & sizing of EPS

INTRODUCTION / EPS GENERAL INFORMATION

/// System drivers / Missions

/ (LIFE) DURATION

- From few minutes (launchers) to 15 years (GEO satellites)
- Ageing drifts shall be assessed on each EPS constituent / Even some manufacturers may not be qualified for long term missions (e.g. ABSL batteries)
- Impact on total radiation dose & nb of thermal cycles

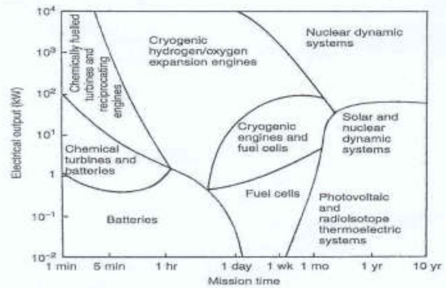


Figure 10.1 Power outputs: mission duration relationship between energy source and appropriate operational scenario [2] (From Angrist, S. W. (1982) *Direct Energy Conversion*, 4th edn, Copyright Allyn and Bacon, New York)

/// Reliability requirements

/ EPS MAY BE REQUESTED TO BE

- SPF (single point failure) free

- No single failure may lead to the loss of mission
- Note: for human mission, no combination of two failures may lead to the loss of mission

- Not reliable

- E.g.: in µSAT, any failure may lead to the loss of mission
- -> Important impact on system architecture (definition of redundancy) and on system cost

INTRODUCTION / EPS GENERAL INFORMATION

///System drivers / Missions

ENERGY BUDGET

- Mission profiles
- Payload needs
  - TV broadcasting points a zone of the Earth
  - Science satellites may point any zone of the sky
  - Military satellites may point any zone of the earth and shall be very agile
- Max and Mean power (in sunlight and in eclipse)
- Orientation (attitude) of the satellite. The attitude constraints directly drive the sizing of the primary and secondary sources: impacts on
  - Eclipse duration
  - SA flux
  - Payload power available (in sunlight and in eclipse)
  - Definition of recovery / safety attitudes of the S/C
  - …

INTRODUCTION / EPS GENERAL INFORMATION

/// EPS equipments glossary

Equipment	
Battery Charge Regulator	BCR
Battery Discharge Regulator	BDR
Begin Of Life	BoL
Converter	CV
Depth Of Discharge	DoD
End of Charge	EoC
End of Discharge	EoD
End Of Life	EoL
Electrical Power Subsystem	EPS
Fold-back Current Limiter	FCL
Latching Current Limiter	LCL

Equipment	
Launch and Early Orbit Phase	LEOP
Maximum Peak Power Tracking	MPPT
Power Conditioning Unit	PCU
Power Conditioning & Distribution Unit	PCDU
Power Sub-System	PSS
Regulated bus	RB
Sequential Switching / Shunt Regulator	S3R
Solar Array	SA
Solar Array Drive Mechanism	SADM
State of Charge	SoC
Unregulated Bus	URB

INTRODUCTION / EPS GENERAL INFORMATION

/// EPS in practice (1)

/// TELECOM 2 (1991)

/// Telecommunication – P = 3 kW

TELECOM 2	Mass (kg)	Satellite mass ratio
Satellite dry mass	1100	100 %
Power Conditioning System (incl. SADM)	43	4 %
Distribution	21	2 %
Battery NiH2	132	12 %
Solar Array	100	9 %
Power TOTAL	**296**	**27 %**

INTRODUCTION / EPS GENERAL INFORMATION

/// EPS in practice (2)

JASON 1 (2001) Mini satellite

Oceanographic Observation satellite – P = 500 W

Jason 1	Mass (kg)	Satellite mass ratio
Satellite dry mass	472	100 %
Power Conditioning System (incl. SADM)	10	2 %
Distribution	29	6 %
Battery NiCd	45	10 %
Solar Array	42	9 %
Power TOTAL	**126**	**27 %**

INTRODUCTION / EPS GENERAL INFORMATION

/// EPS in practice (3)

DEMETER (2004) Micro Satellite

Science (Geodesy) satellite – P = 110 W

DEMETER	Mass (kg)	Satellite mass ratio
Satellite dry mass	110	100 %
Power Conditioning System (incl. SADM)	6.5	6 %
Battery Li-Ion	4	4 %
Solar Array	6.5	6 %
Power TOTAL	**17**	**16 %**

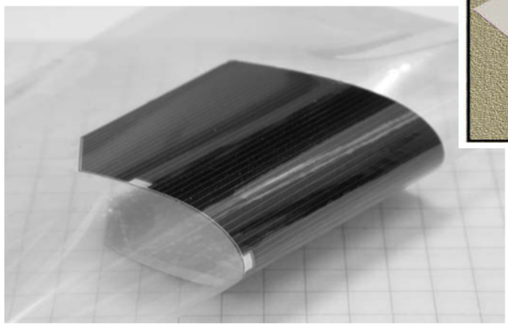
2. PRIMARY POWER SOURCES

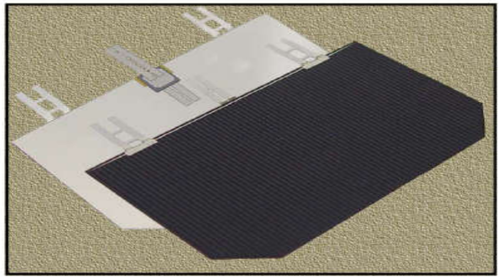
- SOLAR CELLS & SOLAR ARRAYS
- FUEL CELLS
- RTG
- OTHERS

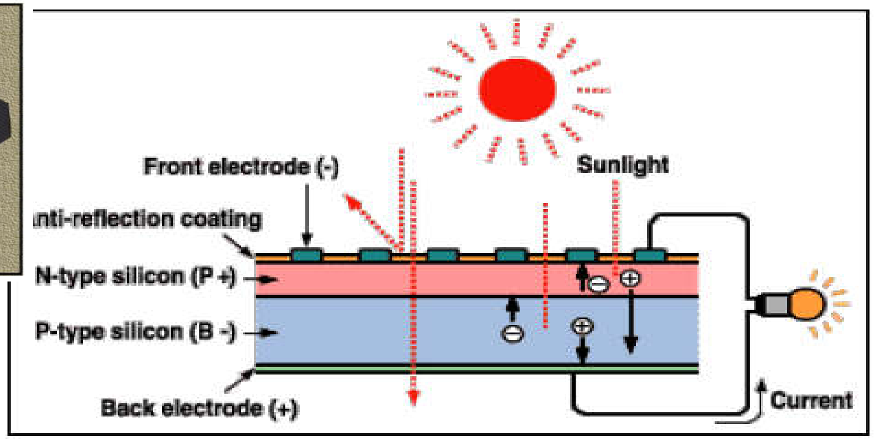
PRIMARY POWER SOURCES/ SOLAR CELLS & ARRAYS

/// SA cells

- **A SOLAR CELL IS COMPOSED OF A SEMI-CONDUCTOR MATERIAL AND CONVERTS PHOTONS TO ELECTRONS**
- **PHOTO-VOLTAÏC EFFECT**
  - The solar flux is reflected, absorbed by the solar cell or crosses it
  - Every absorbed photon whose energy is greater than semi-conductor gap is going to release an electron and to create a positive « hole » (lack of electron). This electron is part of the crystalline network
  - Photons with excessive energy dissipate it as heat in the cell, leading to reduced efficiency
  - An electrical field is introduced in the cell in order to separate this pair of opposite charges





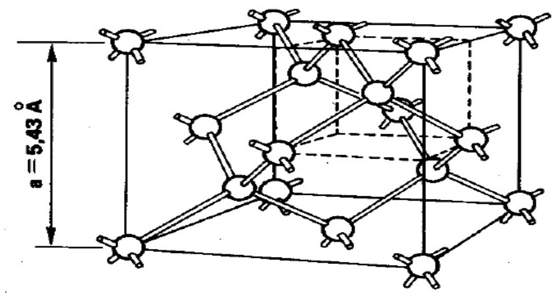


PRIMARY POWER SOURCES/ SOLAR CELLS & ARRAYS

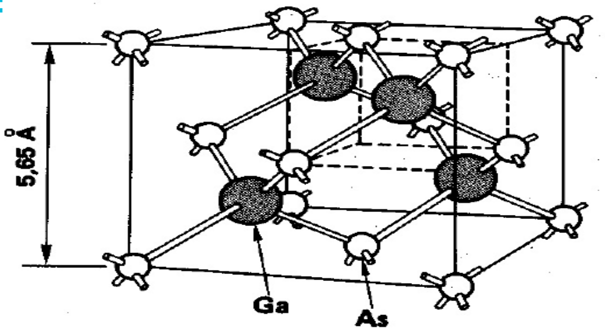
/// Semi-conductors properties

MOST COMMON SEMI-CONDUCTORS: SILICIUM AND ARSENIDE

- Cubic crystalline structures

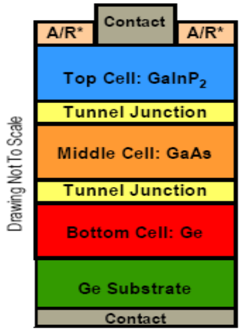


Silicium



Arsenide Gallium

- Method of GaAs Growth: Metal Organic Vapor Phase Epitaxy
- N-type contact (upper surface of the cell): multi-finger arrangement
  - Efficient current collection
  - Good optical transparency
  - Connected at a bar along one edge of the cell

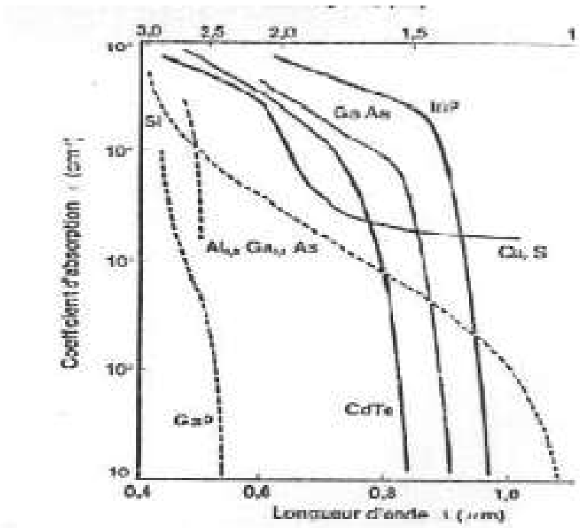


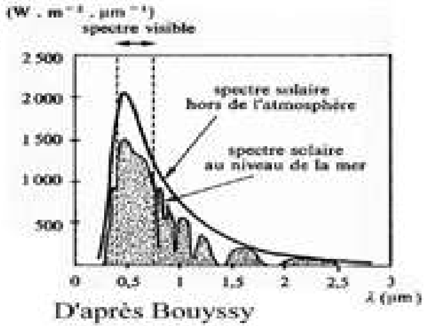
*A/R: Anti-Reflective Coating

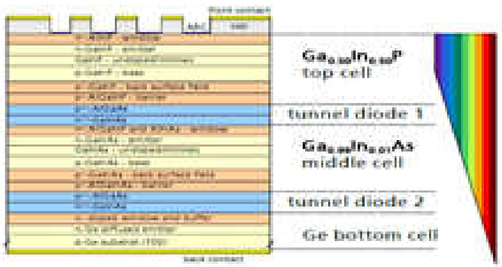
PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

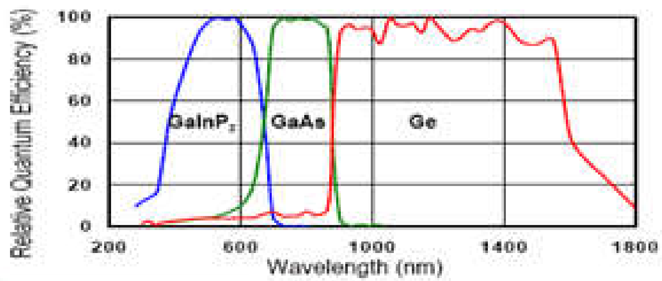
/// Solar flux

SEMI-CONDUCTOR GAP IS CHOSEN TO FIT WITH SPACE LIGHT WAVELENGTH







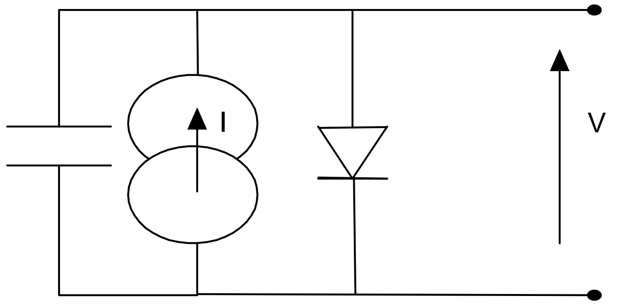


PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Equivalent circuit diagram

/ EACH SOLAR CELL IS EQUIVALENT TO

- a current source in parallel with
- a capacitor (variable) and
- a diode



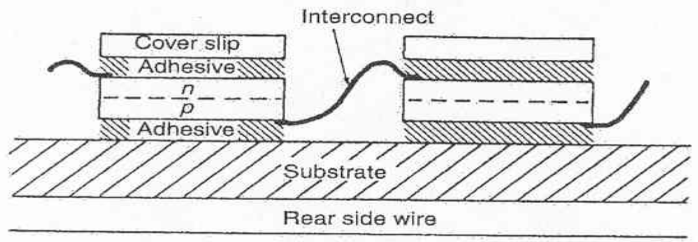
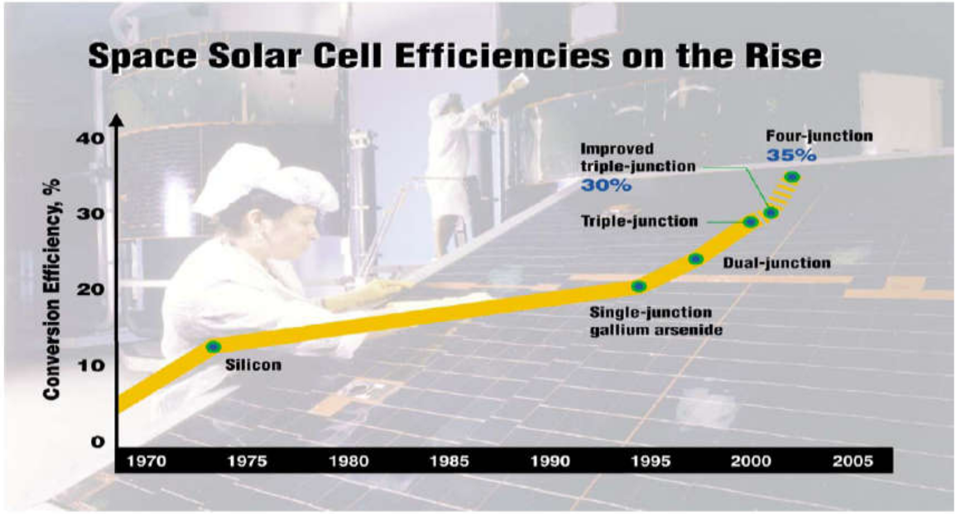
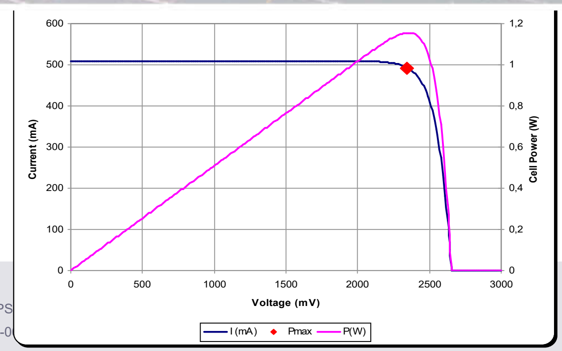


Figure 10.3 Schematic of a typical solar cell assembly

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// SA cell efficiency & characteristics



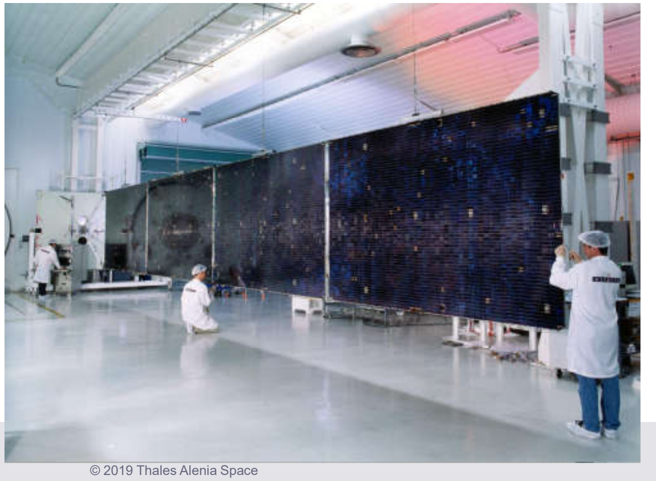


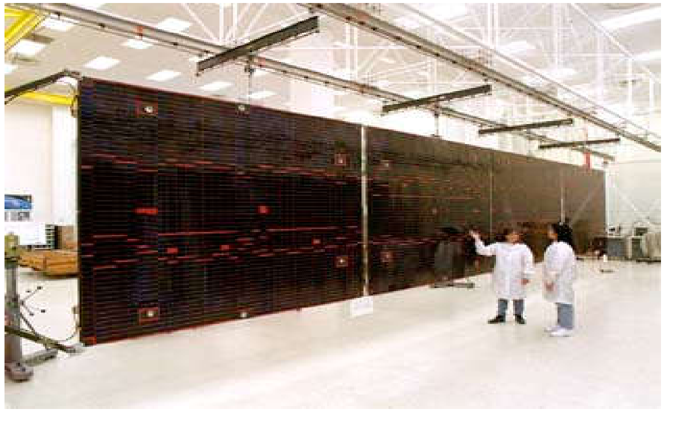
Azurspace 3G28 GaAs Solar Cell - European Epiwafer					
Item	**Unit**	**Description & Attributes**			
Cell	-	3G28/150-8438 from Azurspace covreglassed with 100µm CMG type coverglass from QIOPTIQ			
ion	*mm*	38,8 x 87,7			
e Area	*cm²*	30,629			
ss	*µm*	150			
ight	*mg*	2634			
Electrical Characteristics @ 25,0°C under 1AM0)					
	mA/cm²	16,626			
	mV	2 649			
	mA/cm²	16,081			
	mV	2 345			
Remaining Factors					
		BOL	**1,00E+14 1MeV e- / cm²**	**1,00E+15 1MeV e- / cm²**	**3,00E+15 1MeV e- / cm²**
	-	1,000	0,998	0,963	0,878
	-	1,000	0,970	0,934	0,909
RI_{MP}	-	1,000	0,992	0,955	0,867
RV_{MP}	-	1,000	0,973	0,930	0,905
Temperature Coefficients					
Applicable for Temperature = 50°C		**BOL**		**1,00E+15 1MeV e- / cm²**	**3,00E+15 1MeV e- / cm²**
dI_{SC}/dT	*mA/cm²/°C*	1,079E-02		1,246E-02	1,458E-02
dV_{OC}/dT	*mV/°C*	-6,06		-6,46	-6,62
dI_{MP}/dT	*mA/cm²/°C*	9,052E-03		1,087E-02	1,180E-02
dV_{MP}/dT	*mV/°C*	-6,68		-6,90	-7,09

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

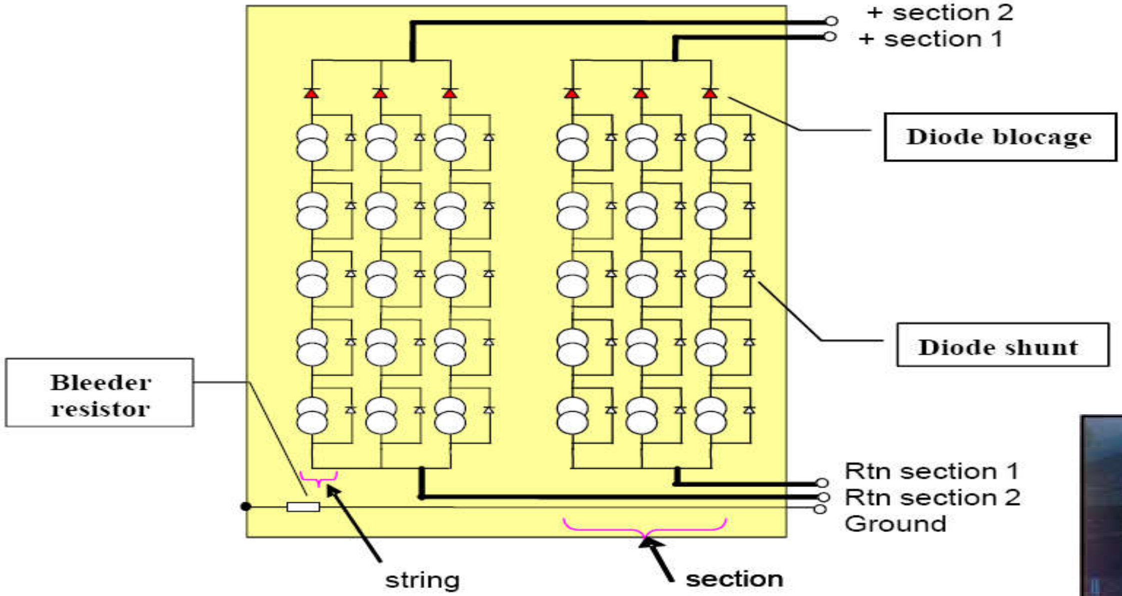
///Solar arrays

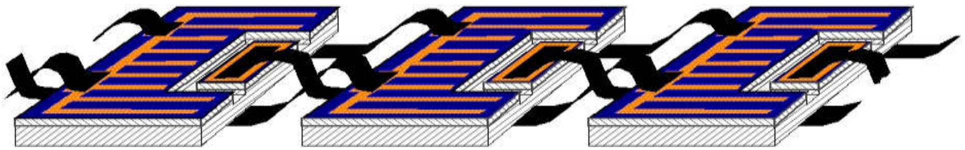
- **A SOLAR CELL PRODUCES SOME HUNDREDS OF MILLIWATTS**
- **A SOLAR ARRAY (SA) IS COMPOSED OF THOUSANDS CELLS ASSEMBLED IN SERIES AND IN PARALLEL**
  - The network = cells + interconnections + cabling + diodes
  - A string = assembling of cells in series to obtain the desired voltage
  - A section = strings in parallel to obtain the desired current
- **SECTIONS ARE INDEPENDENT**





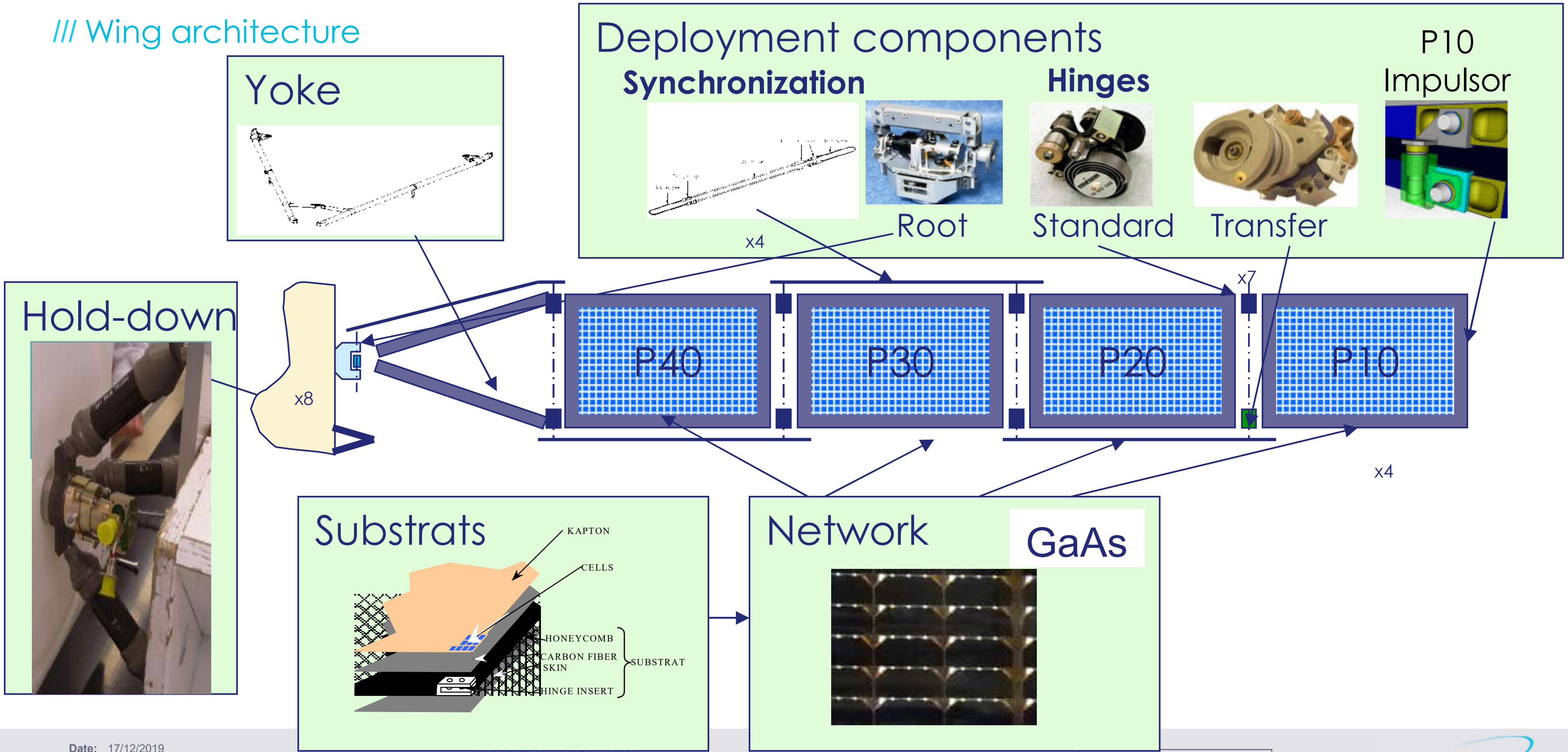
PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS





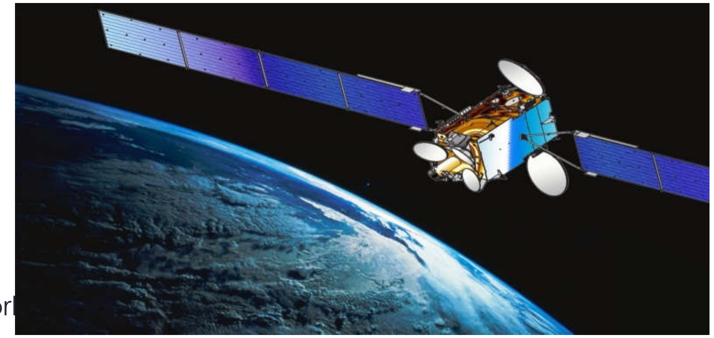
PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Wing architecture



PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Solar arrays – Types

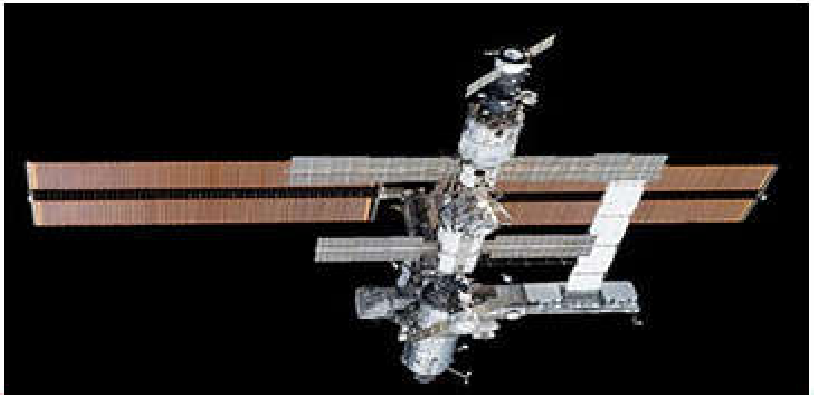


- **FIXED**
  - Solar cells are glued on the structure of the satellite
  - The power is limited by the surface of the satellite

- **DEPLOYABLE (FIXED)**
  - Solar cells are glued on flaps (folded at launch and deployed in or
  - Difficult to manage the attitude constraints

- **DEPLOYABLE AND MOBILE**
  - 1-degree of freedom

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS



PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Panel, glue, coverglass, …

/ SUBSTRATE

- Kapton with glass – or carbon- reinforcement

/ GLUE, ADHESIVE

- Fix SA cell on SA panel
- Fix the coverglass on the cell
- Ensure electrical & thermal conductivity

/ PANEL (HONEYCOMB)

- Support SA cells
- Transfer heat to bottom side
- Face high thermal gradient
- Be compatible with deployment and orientation mechanisms

/ COVERGLASS

- Protect SA cell against ATOX
- Protect SA cell against radiation
- Limit the UV flux to the adhesive layer and to the cell by allowing suitable wavelength selection, via a good optical coupling (between free-space and glass & between glass and adhesive)

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// TAS-B - PVA Factory4.0: our current challenges

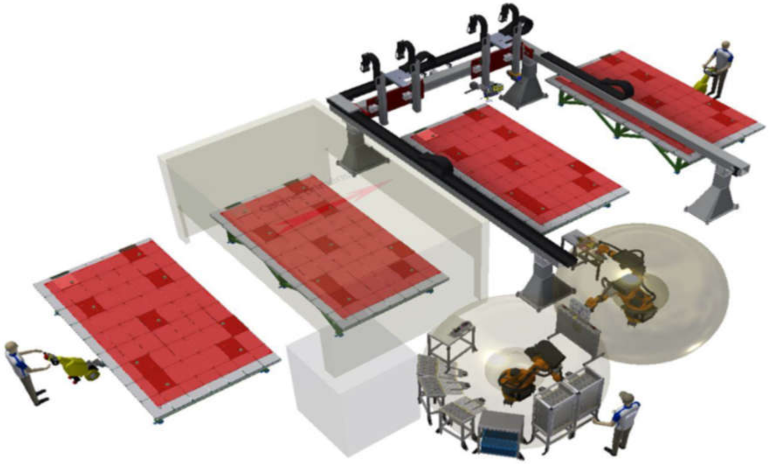
AUTOMATION OF CRITICAL PROCESSES: GLUE DISPENSE, LAY-DOWN, WELDING

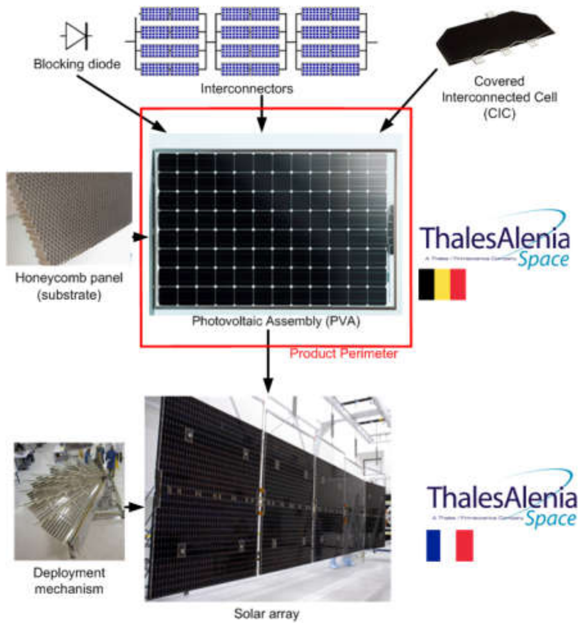
- In-line testing, control and traceability

AIDING STATIONS FOR HARNESSING LEVERAGING 4.0 TECHNOLOGIES

- « Augmented » operator focus on manufacturing operations

AUTOMATION OF ACCEPTANCE TEST EXECUTION





PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Efficiency degradation factors

- CELLS MISMATCH & CALIBRATION
- MISSION LIFETIME
  - Loss of power: 1% to 2% every year (depends of the orbit)
- RADIATION EFFECTS

Radiation Degradation
(Fluence 1MeV Electrons/cm^2)

Parameters	1×10^{14}	5×10^{14}	1×10^{15}
Imp/Imp_0	0.99	0.98	0.96
Vmp/Vmp_0	0.94	0.91	0.89
Pmp/Pmp_0	0.93	0.89	0.86

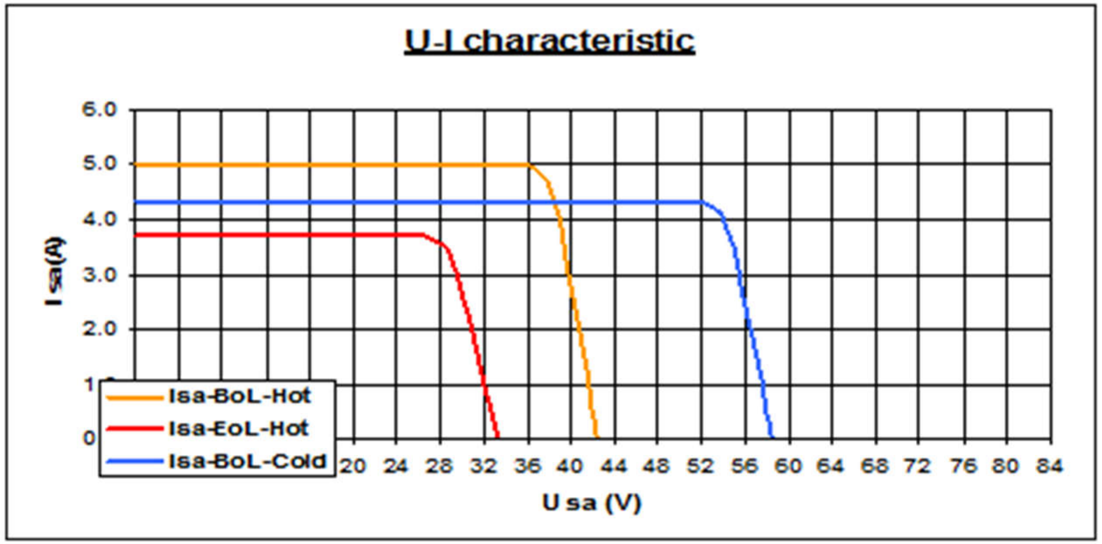
Illustration SPECTROLAB

- UV
- METEORITE IMPACT
- ATOX DENSITY
  - Aggressive and corrosive environment (tied to the LEO) on cover glass protection and on exposed interconnection (oxidation of silver and then increase of resistivity)

	Input Factor	TRANSFERT Phase	GEO Phase BOL	GEO Phase EOL	I_{MAX} Case
a.	*Cell Mismatch*	0.99 (-1%)	0.99 (-1%)	0.99 (-1%)	1.01 (+1%)
b.	*Cell Calibration*	0.97 (-3%)	0.97 (-3%)	0.97 (-3%)	1.03 (+3%)
c.	*Best Production Case*	1 (0%)	1 (0%)	1 (0%)	1.015 (+1.5%)
d.	*Thermo-Optical Coefficients*	1* (0%)	1* (0%)	1* (0%)	1* (+0%)
e.	**RSS Calculation:** $RSS_1 = 1 - \frac{\sqrt{a^2+b^2+c^2+d^2}}{100}$ **Excepted for I_{MAX}**	0.968 (-3.2%)	0.968 (-3.2%)	0.968 (-3.2%)	1.055 (+5.5%)
f.	**Coverglass Gain/Loss**	0.99 (-1%)	0.99 (-1%)	0.99 (-1%)	0.995 (-0.5%)
g.	*UV + Micro Meteorites 0.9975 / an - 0.25% / an*	1 (0%)	1 (0%)	0.9625 (-3.75%)	1 (0%)
h.	*Random Failure*	1 (0%)	1 (0%)	1 (0%)	1 (0%)
i.	*Solar Angle*	1 (0%)	1 (0%)	1 (0%)	1 (0%)
j.	*Pointing Error due to disorientation and internal Solar Array error*	1 (0%)	1 (0%)	1 (0%)	1 (0%)
k.	**Total Life Loss Calculation:** $LifeLoss = g + h + i + j$	1 (0%)	1 (0%)	0.9625 (-3.75%)	1 (0%)
l.	**Global Loss Factor:** $Global\_Loss = 1 - e - f - k$	0.957 (-4.3%)	0.957 (-4.3%)	0.919 (-8.1%)	1.05 (+5%)

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Optimal working point – at max. available power



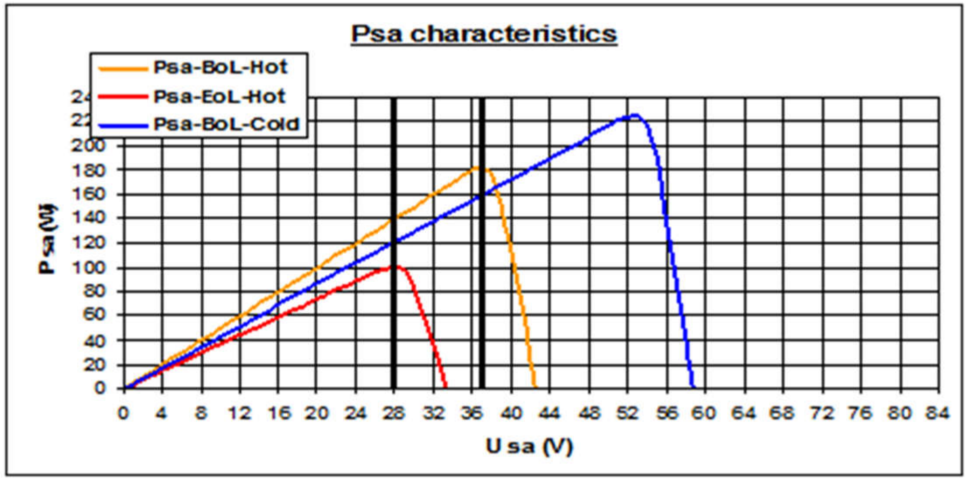
Pmax is largely depending of temperature & ageing

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Temperature is linked to

THE INCOMING FLUX
- Direct solar flux
- Albedo (ratio between reflected flux vs incoming flux)
- IR flux of the earth

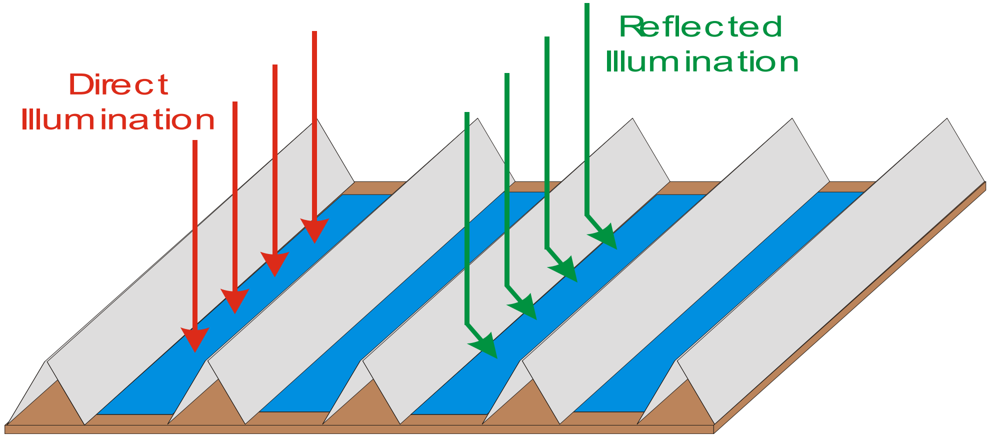
THE OUTCOMING FLUX
- Flux reflected by the cells
- Power delivered to the satellite
- IR flux of the front and rear part of the SA



PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Concentrators / Advantages

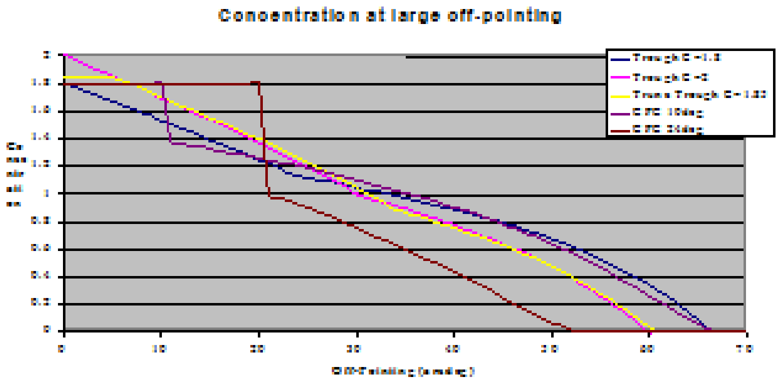
- **CONCENTRATE SA FLUX ON SA CELLS**
- **REDUCE SA CELLS SURFACE**
- **BASED ON REFLECTORS OR ON LENS**

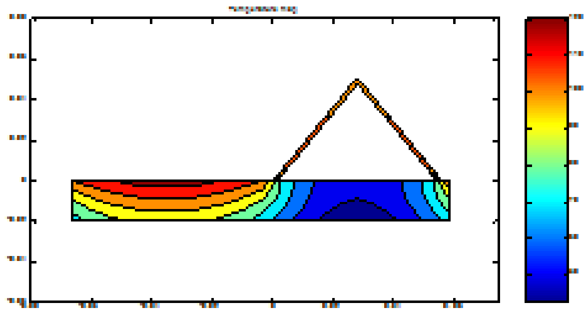


PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Concentrators / Drawbacks

- **NOT COMPATIBLE WITH LARGE OFF-POINTING ANGLE**
  - Oblique rays can hit the reflectors two times and then they may be reflected back to space
  - Off-pointing (hors pointage) property of SA concentrator is not compliant with un-stabilized S/C
- **INDUCES HIGHER THERMAL CONSTRAINTS ON CELLS AND SA PANEL**





- **OUTGASSING MAY BECOME CRITICAL**

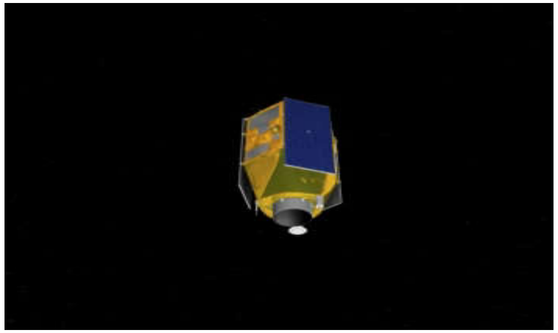
PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

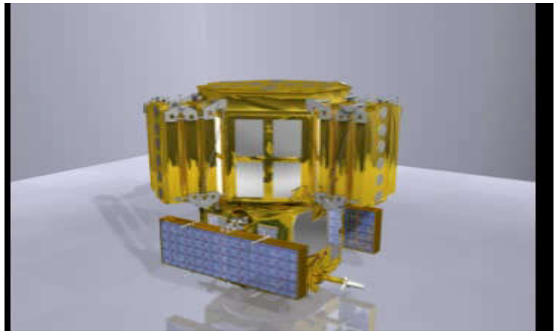
/// Solar Arrays – mechanisms (hold-down & release)

SA ARE FOLD (REPLIÉS) DURING LAUNCH

DEPLOYMENT IS

- Initiated by pyro actuation (or thermal knifes)
- Controlled by the use of hinge mechanisms

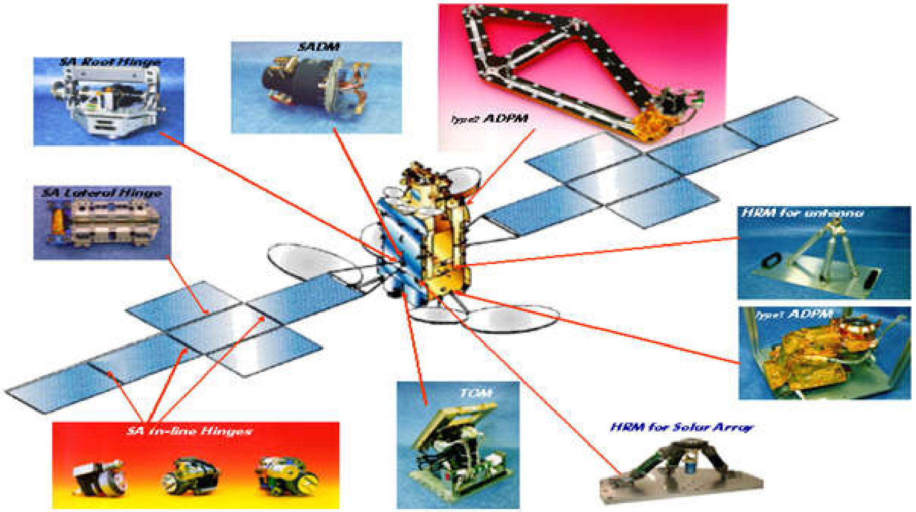




PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Solar Arrays – mechanisms (orientation)

- MOBILE SA IS CONTROLLED BY SADM (SOLAR ARRAY DEPLOYMENT MOTOR)
- CURRENT IS TRANSFERRED TO S/C MAIN PART VIA BAPTA (BEARING AND POWER TRANSFER ASSEMBLY)
- TENSIONING WIRES – ACHIEVE MINIMUM FUNDAMENTAL FREQUENCY OF THE ARRAY (AOCS CONSTRAINTS): (ATTITUDE & ORBIT CONTROL SYSTEM)



_ Illustration Thales Alenia Space

PRIMARY POWER SOURCES / SOLAR CELLS & ARRAYS

/// Solar arrays – performances

/ TYPICAL PERFORMANCES AFTER 15 YEARS IN GEO

- Silicium: 100 W / m2
- High efficiency silicium: 130 W / m2
- AsGa (mono junction): 170 W / m2
- AsGa double junction: 200 W / m2
- AsGa triple junction: 240 W / m2

/ POWER / KG:

- Silicium or AsGa/Ge: 40-50 W/kg
- Multi junctions: 50-60 W/kg

PRIMARY POWER SOURCES / FUEL CELLS

/// Electromechanical devices performing a controlled chemical reaction (oxydation) to derive electrical energy (rather than heat energy)

ADVANTAGES

- Minimal thermal changes
- Compact and flexible solution
- Production of water (manned mission)

DRAWBACKS

- Need of fuels: hydrogen & oxygen yielding water as the reaction product

USED FOR SHUTTLE ORBITER, LUNAR ROVER, …

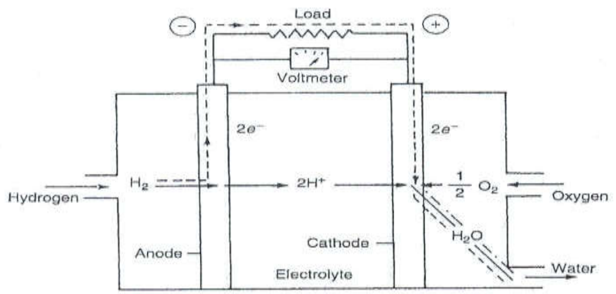


Figure 10.10 Schematic of a hydrogen/oxygen fuel cell. At the anode–electrolyte interface, hydrogen dissociates into hydrogen ions and electrons. The hydrogen ions migrate through the electrolyte to the cathode interface where they combine with the electrons that have traversed the load [2] (From Angrist, S. W. (1982) *Direct Energy Conversion*, 4th edn, Copyright Allyn and Bacon, New York)

PRIMARY POWER SOURCES / FUEL CELLS

/// Typical current-voltage curve for a hydrogen/oxygen fuel cell

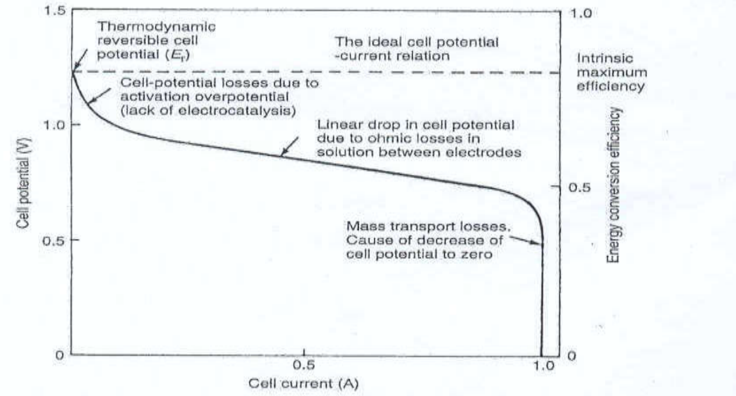


Figure 10.11 Typical cell potential and efficiency–current relation of an electrochemical electricity producer showing regions of major influence of various types of overpotential losses (Source [10])

/// Performance summary of fuel cells for space use

System	Specific power (W/kg)	Operation	Comment
Gemini	33	240 h	Not drinking water
Apollo	25		Operated at 505 K 24 h start-up / 17 h shutdown
Shuttle	275	2500 h	15 min start-up / instantaneous shutdown
SPE technology	110 – 146	> 40000 h	
Alkaline technology	367	> 3000 h	
Alkaline technology	110	> 40 000 h	
Goal (lightweight cell)	550		

PRIMARY POWER SOURCES / FUEL CELLS

///Use of fuel cell as « secondary power source »

- **REGENERATIVE FUEL CELLS (100 KW SYSTEM POWER) ELECTROLYZE OF WATER IS PERFORMED DURING THE ‘CHARGE’ CYCLE THANKS TO PRIMARY SOURCE POWER**

- **ADVANTAGE**
  - Lower SA power need thanks to judicious sizing of the fuel

- **DRAWBACK**
  - Lower efficiency (50 – 60 %) than battery

- **INTERESTING FOR LEO OPERATIONS WHERE ATMOSPHERIC DRAG (TRAÎNÉE) IS IMPORTANT (VERY LOW ORBITS) -> REDUCTION OF PROPELLANT USED FOR ORBIT CONTROL**

PRIMARY POWER SOURCES / RTG (RADIOISOTOPE THERMOELECTRIC GENERATOR)

///Deep-space missions (further than Mars) or Military use

- **LONG TIME MISSIONS, NOT-COMPATIBLE WITH FUEL CELLS**
- **FAR FROM SUN, NOT-COMPATIBLE WITH SA**
  - Decrease of SA flux partially compensated by increased of cell efficiency due to decrease of temperature (rE/rSC)1.5
    -> Use of radioactive decay process, use of thermoelectric effect

///Thermoelectric effect

- **GENERATION OF A VOLTAGE BETWEEN (SEMI-CONDUCTOR) MATERIALS MAINTAINING A TEMPERATURE DIFFERENCE. POWER FUNCTION OF:**
  - Absolute t° of hot junction
  - T° difference between materials
  - Properties of materials
- **LOW EFFICIENCY (< 10 %)**
  -> REMOVING WASTE HEAT MAY BE AN ISSUE
- **HEAT SOURCE: SPONTANEOUS DECAY OF A RADIOACTIVE MATERIAL, EMITTING HIGH-ENERGY PARTICLES, HEATING ABSORBING MATERIALS**

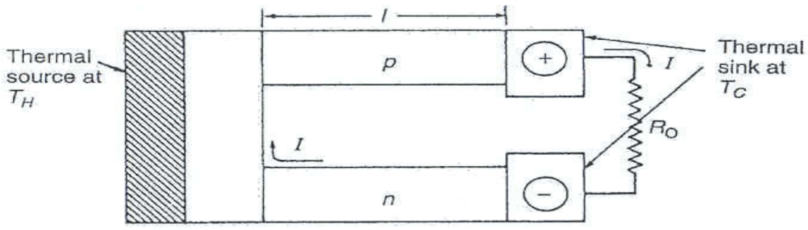


Figure 10.12 Schematic diagram of a semiconductor radioisotope generator (From Angrist, S. W. (1982) *Direct energy conversion*, 4th edn, Copyright Allyn and Bacon, New York)

PRIMARY POWER SOURCES / RTG

/// Advantages

- POWER PRODUCTION INDEPENDENT OF S/C ORIENTATION & SHADOWING
- INDEPENDENCE OF DISTANCE FROM SUN
- LOW POWER LEVEL MAY BE PROVIDED FOR LONG TIME PERIOD
- NOT SUSCEPTIBLE TO RADIATION DAMAGE
- COMPATIBLE WITH LONG ECLIPSE (E.G. LUNAR LANDERS)

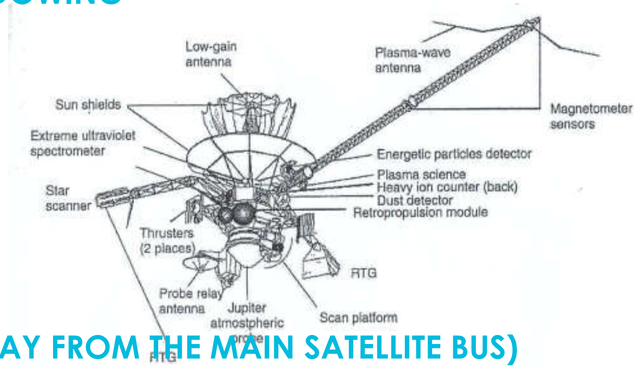


Figure 10.13 The Galileo spacecraft configuration, showing the position of the RTG sources (Courtesy of NASA/JPL/Caltech)

/// Drawbacks

- AFFECT THE RADIATION ENVIRONMENT OF S/C (DEPLOYMENT AWAY FROM THE MAIN SATELLITE BUS)
- RADIOACTIVE SOURCE INDUCE SAFETY PRECAUTIONS IN AIT
- HIGH T° OPERATION REQUIRED -> IMPACT THERMAL ENVIRONMENT OF S/C
- INTERFERE WITH PLASMA DIAGNOSTIC EQUIPMENT (SCIENTIFIC MISSIONS)
- ENVIRONMENTAL RISK IN CASE OF LAUNCH FAILURE OR S/C CRASH

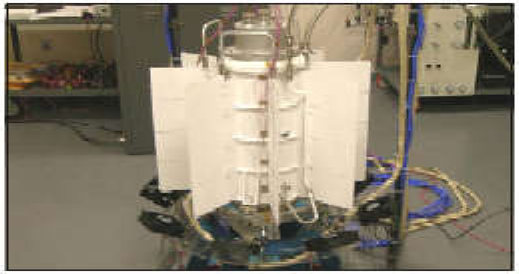
PRIMARY POWER SOURCES / RTG & OTHERS

///Example of RTG

CASSINI (SATURN MISSION)	628 W	195 W/KG
GALILEO PROBE/ULYSSES	285 W	195 W/KG
NIMBUS/VIKING/PIONNER	35 W	457 W/KG
APOLLO LANDER	25 W	490 W/KG
MARS SCIENCE LABORATORY	120 W	416 W/KG

/// Nuclear fission

- FISSIBLE MATERIAL (E.G. URANIUM-235) USE OF NUCLEAR FISSION PROCESS (AS FOR TERRESTRIAL NUCLEAR POWER PLANTS)
- USED TO DRIVE THERMOELECTRIC CONVERTER AS RTG



MMRTG Engineering Unit

PRIMARY POWER SOURCES / OTHERS

///Solar heat

- **USE OF SUN ENERGY TO DRIVE A HEAT ENGINE AND THEN A ROTARY CONVERTER TO ELECTRICITY OR A THERMOELECTRIC CONVERTER**
- **CONCEPT INTERESTING FOR SPACE STATION**
  - Reduced drag (reducing area of SA panels)
  - Reduced maintenance effort

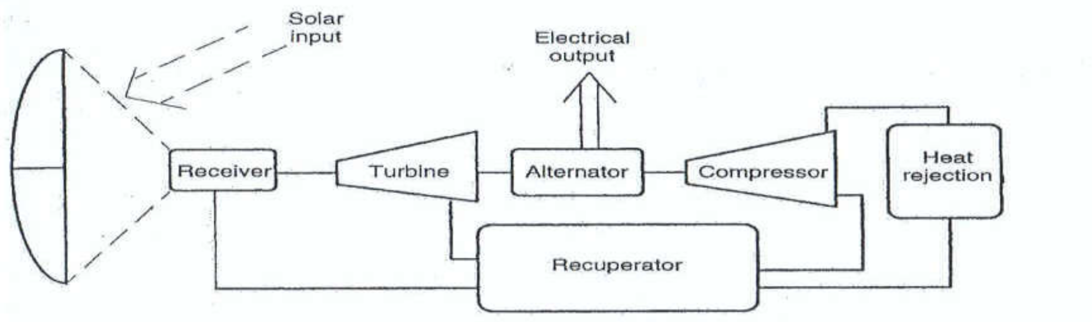
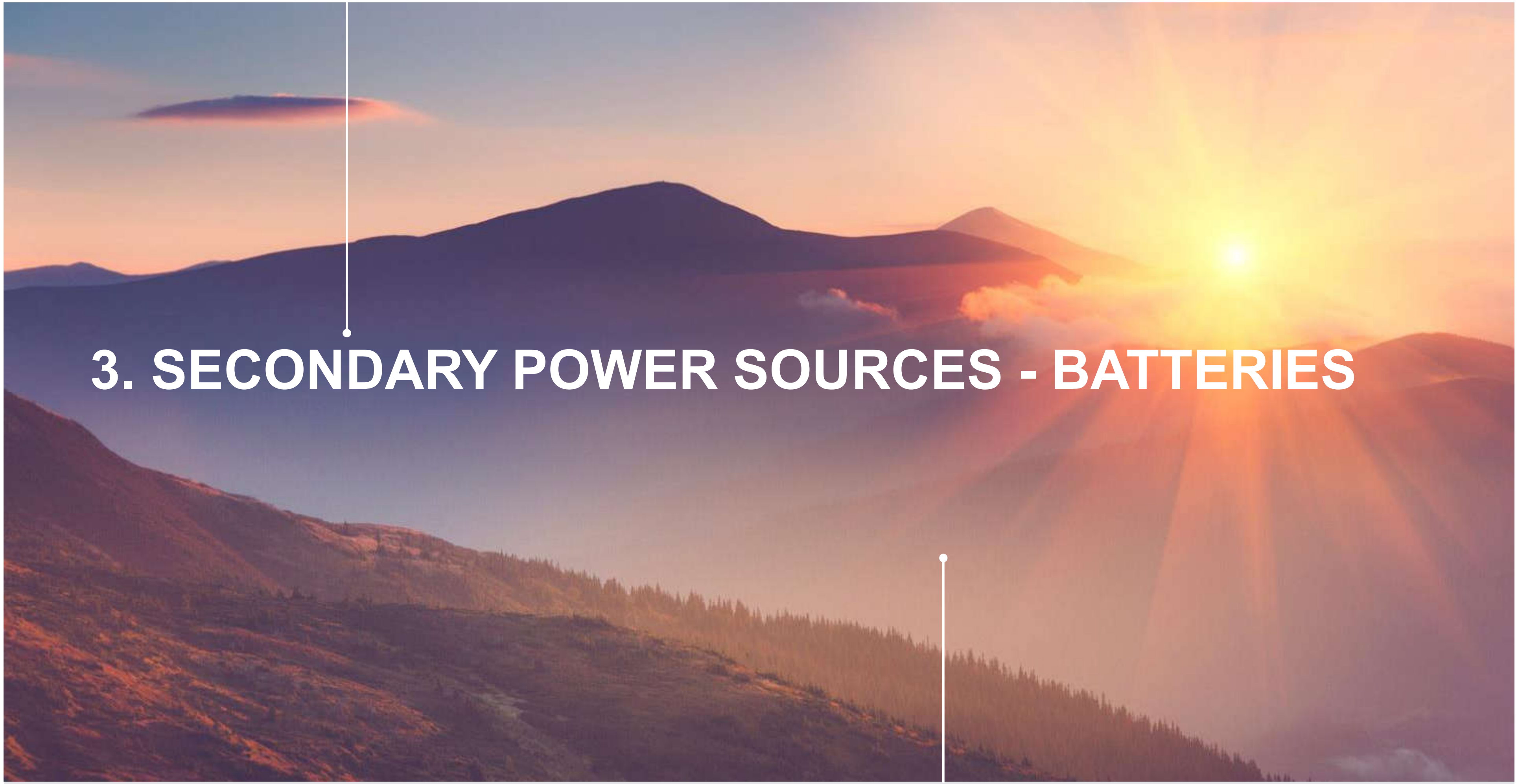


Figure 10.14 Solar dynamic Brayton cycle



3. SECONDARY POWER SOURCES - BATTERIES

PRIMARY POWER SOURCES / OTHERS

/// Solar heat

- **USE OF SUN ENERGY TO DRIVE A HEAT ENGINE AND THEN A ROTARY CONVERTER TO ELECTRICITY OR A THERMOELECTRIC CONVERTER**
- **CONCEPT INTERESTING FOR SPACE STATION**
  - Reduced drag (reducing area of SA panels)
  - Reduced maintenance effort

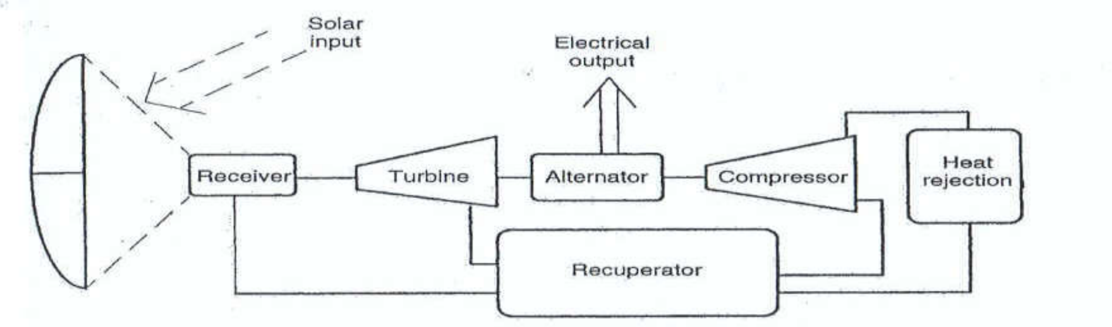
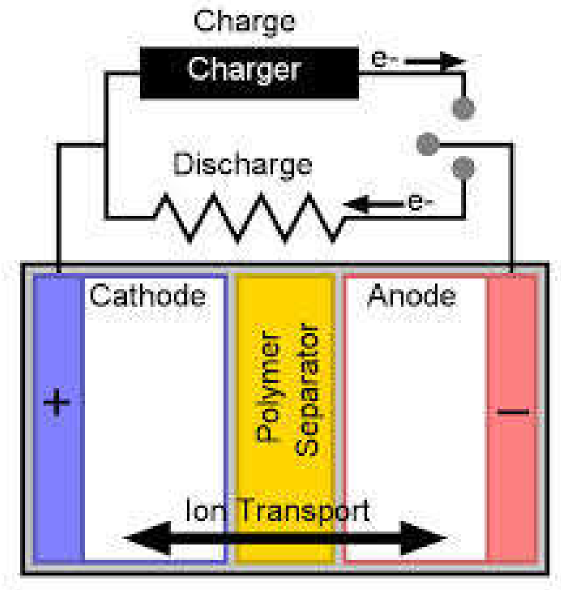


Figure 10.14 Solar dynamic Brayton cycle

SECONDARY POWER SOURCES

/// Accumulators

- ELECTROMECHANICAL DEVICES PERFORMING A CONTROLLED CHEMICAL REACTION TO DERIVE ELECTRICAL ENERGY
- DURING DISCHARGE, THE POSITIVE ACTIVE MATERIAL IS REDUCED, ABSORBING ELECTRONS, AND THE NEGATIVE MATERIAL IS OXIDIZED, RELEASING ELECTRONS. IONS ARE DISSOLVED INTO AN ELECTROLYTE AND TRANSFERRED THROUGH A SEPARATOR (WHICH IS AN ELECTRIC INSULATOR) TO EQUILIBRATE THE CHARGE.
- IF THE ELECTRODE MATERIALS ARE CHOSEN SO THAT THESE REACTIONS ARE REVERSIBLE, THE CELL CAN BE RECHARGED. IT IS CALLED SECONDARY (I.E. RECHARGEABLE).

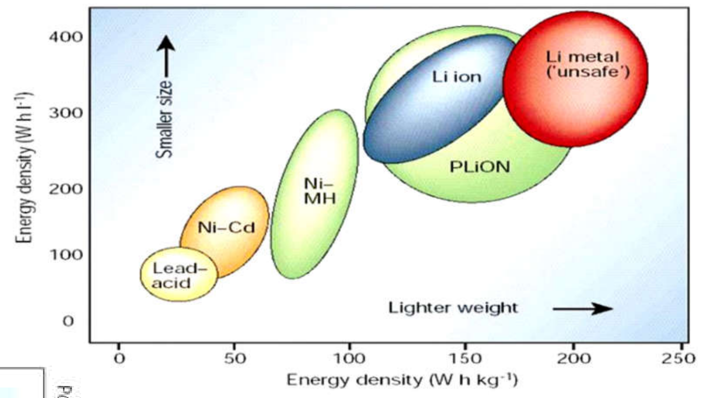


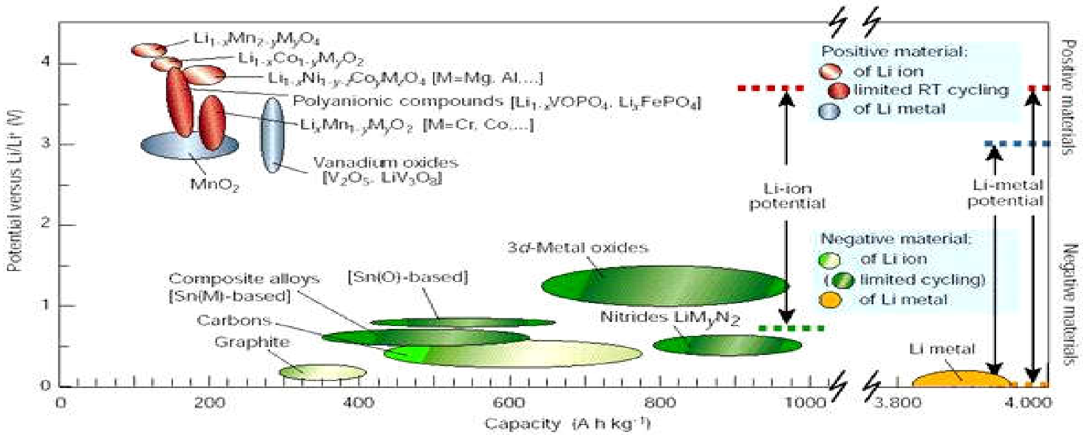
SECONDARY POWER SOURCES

/// Accumulators

CRITICAL PARAMETERS

- Charge/discharge rate
- Depth of Discharge
- Extent of over-discharging
- Thermal sensitivity to each of these parameters

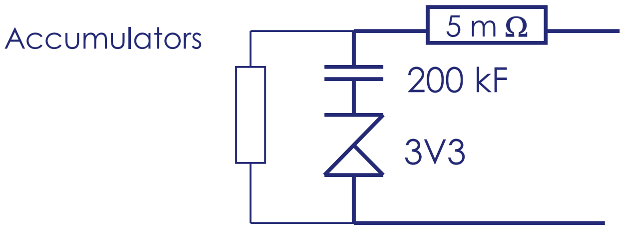


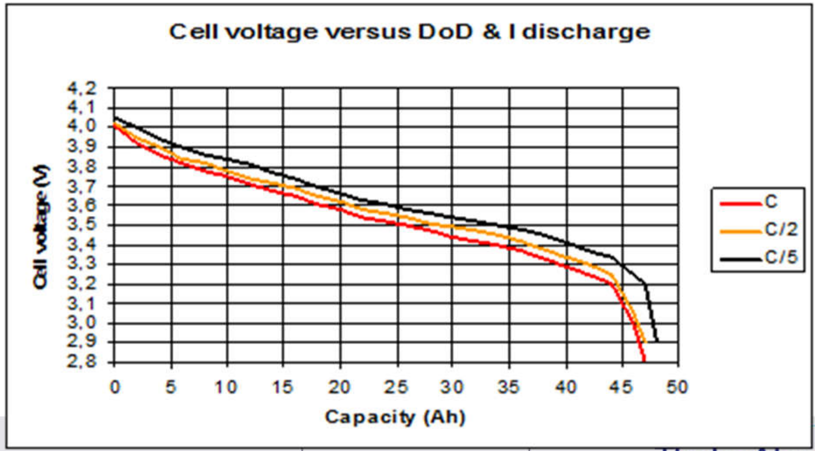


SECONDARY POWER SOURCES

/// Typical Characteristics

- **CAPACITY : A BATTERY'S CAPACITY IS THE AMOUNT OF ELECTRIC CHARGE IT CAN STORE. THE MORE ELECTRODE MATERIAL THERE IS IN THE CELL THE GREATER THE CAPACITY OF THE CELL. A SMALL CELL HAS LESS CAPACITY THAN A LARGER CELL WITH THE SAME CHEMISTRY, AND THEY DEVELOP THE SAME OPEN-CIRCUIT VOLTAGE. CAPACITY IS GIVEN IN A.H (1 A.H = 3600 COULOMB).**
  - 1.5Ah -> 100Ah
- **C RATE: THE C-RATE SIGNIFIES A CHARGE OR DISCHARGE RATE RELATIVE TO THE CAPACITY OF A BATTERY IN ONE HOUR. FOR AN 1.6 A.H BATTERY, A RATE OF 1C WOULD MEAN A CURRENT OF 1.6 AMP. A C/2 RATE WOULD MEAN A CURRENT OF 0.8 AMP**
- **CELL OPEN CIRCUIT VOLTAGE :**
  DIFFERENCE BETWEEN CELL ELECTRODE POTENTIALS
- **VOLTAGE RANGE**
  - 4.1V -> 3.3V
- **SERIES RESISTANCE**
  - 1mΩ -> 10m Ω
- **LEAKAGE CURRENT**
  - 0mA -> 5mA





SECONDARY POWER SOURCES

/// Comparison of performances

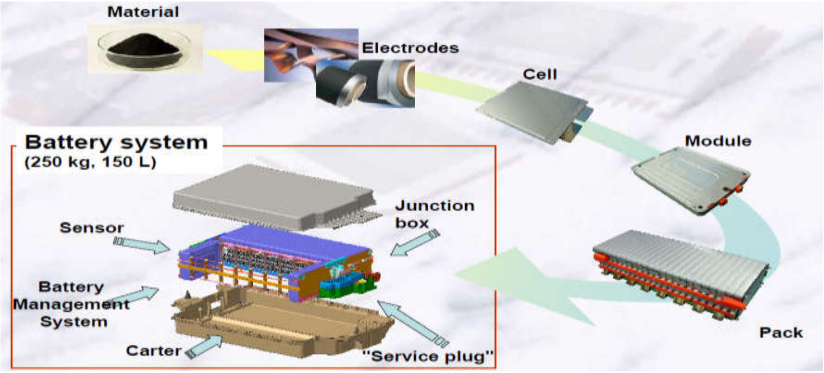
Type	NiCd	NiH2	Li-Ion
Energy/kg (Wh/kg)	30-40	55-65	100-130
Energy/l (Wh/l)	110	80	200-250
Discharge voltage mean (V)	1.25	1.25	3.5
Working temperature (°C)	[-5;+15]	[0;+10]	[+15;+25]
Charge current (A)	⇒C/10 (GEO) ⇒C/2 (LEO)	⇒C/8 (GEO) ⇒0.7C (LEO)	C/10⇒ C/3
Discharge current (A)	⇒2C	⇒C	⇒C
Energy efficiency (%)	75	75	90
Max. voltage (V)	1.55	1.6	4.0
Min. voltage (V)	1.0	1.0	2.7
Capacity (Ah)	4 ⇒ 50	30 ⇒ 350	1.5,2.2,26,40
Life duration in Geo	7 years at 50 % of DoD	15 years at 80 % of DoD	15 years at 80 % of DoD
Life duration in Leo	10 years at 15 % of DoD	5 years at 40 % of DoD	7 years at 30 % of DoD

SECONDARY POWER SOURCES

/// Battery

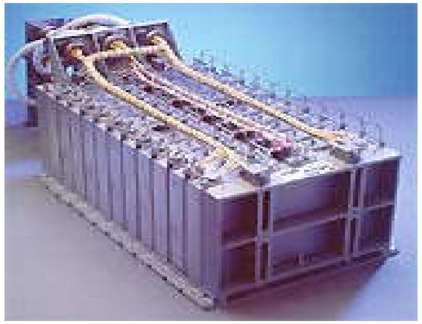
ROLE: SUPPORT THE SOLAR ARRAY DURING

- LEOP phases
- Eclipses
- Loss of sun pointing
- Peak power demands
- …



SERIES / PARALLEL ASSEMBLING OF ACCUMULATOR CELLS

- In series to reach the desired voltage
  - 22V-37V in LEO
  - EUROSTAR 2000: 42.5 V
  - EUROSTAR 3000 & SPACEBUS 3000: 50 V
  - SPACEBUS 4000: 100 V
- In parallel to reach the desired capacity



NICKEL HYDROGEN BATTERY

SECONDARY POWER SOURCES

/// Battery tapering & energy sizing

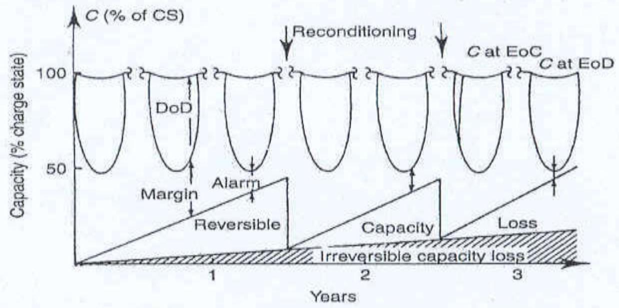
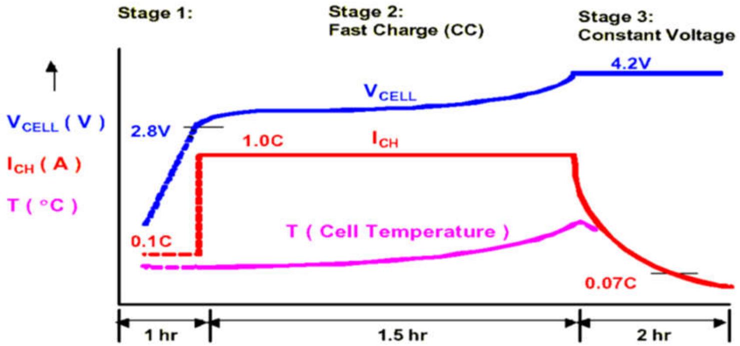
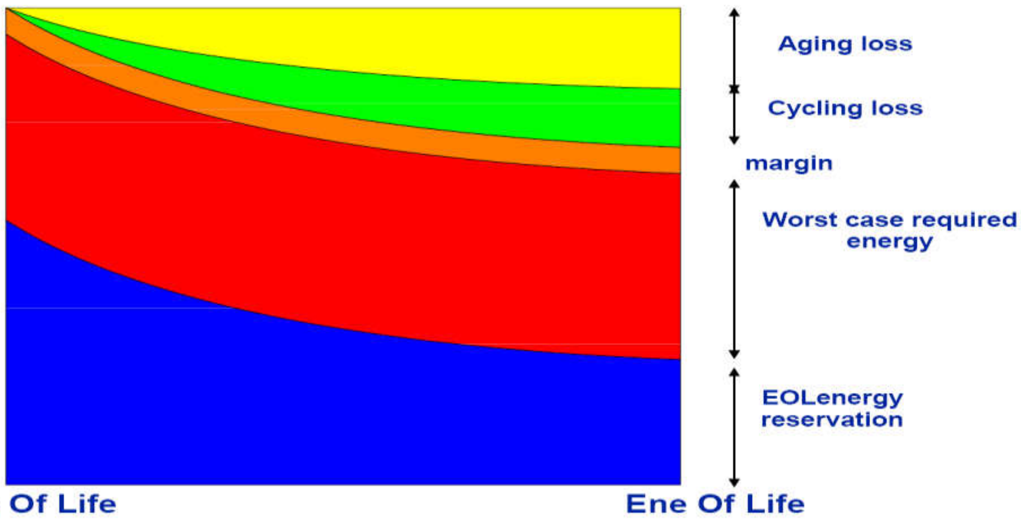


Figure 10.16 Battery reconditioning via complete discharge to improve battery capacity. Both reversible and irreversible capacity loss occurs [17] (Reproduced by permission of European Space Agency and P. Montalenti)





SECONDARY POWER SOURCES

BoL	SAFT NiCd VOS 40	SAFT NiH2 93 AN	SAFT Li-Ion VOS140	SAFT Li-Ion MP76065	SONY Li-Ion 18650HC
Capacity	46 Ah	89 Ah	38.6 Ah	6.1 Ah	1.4 Ah
Mean voltage	1.2 V	1.36 V	3.6 V	3.6 V	3.7 V
Energy	55 Wh	120 Wh	140 Wh	22 Wh	5.2 Wh
Mass	1610 g	2108 g	1107 g	155 g	41.2 g
Energy/kg	34 Wh/kg	57 Wh/kg	126 Wh/kg	141 Wh/kg	126 Wh/kg
Efficiency	70 %	70 %	90 %	90 %	90 %

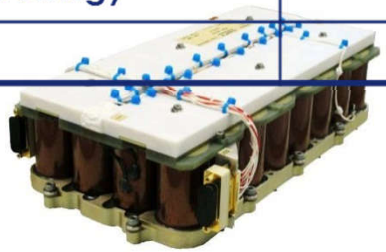
SECONDARY POWER SOURCES

BoL	SPOT-5	EURASIASAT	STENTOR	SKYBRIDGE
Configuration	24s-1p VOS40	27s-1p 93AN	11s-2p VOS140	12s-4p VOS140
Capacity	46 Ah	93 Ah	80 Ah	154 Ah
Mean voltage	29 V	37 V	39.6 V	43 V
Energy	1325 Wh	3415 Wh	3168 Wh	6620 Wh
Mass	47.4 kg	66 kg	34 kg	72 kg
Dimensions	467X261X260mm	863X441X310mm	490X380X290mm	910X520X300mm
Specific energy	28 Wh/kg	52 Wh/kg	93 Wh/kg	92 Wh/kg
Density	42 Wh/l	29 Wh/l	59 Wh/l	47 Wh/l

SECONDARY POWER SOURCES

/// Sampling of batteries

BoL	PLEIADES	µSAT
Configuration	8s-100p 18650HC	8s-10p 18650HC
Capacity	140 Ah	14 Ah
Mean voltage	30 V	30 V
Energy	4200 Wh	420 Wh
Mass	40,4 kg	4 kg
Dimensions	2 x (355 x 295 x 180 mm)	226 x 166 x 95 mm
Specific energy	105 Wh/kg	105 Wh/kg
Density	170 Wh/l	118 Wh/l



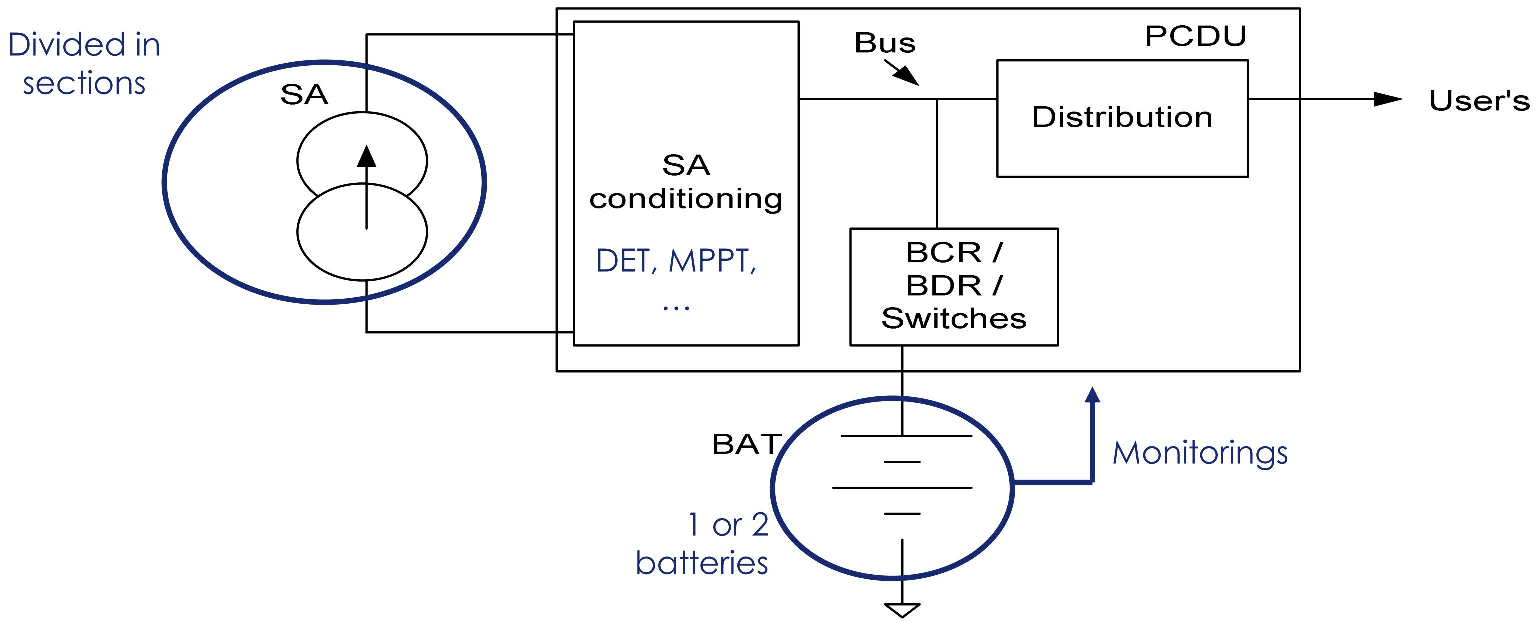
Data CNES

4. POWER MANAGEMENT, CONTROL & DISTRIBUTION

- ARCHITECTURE
- PCU/PCDU

POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

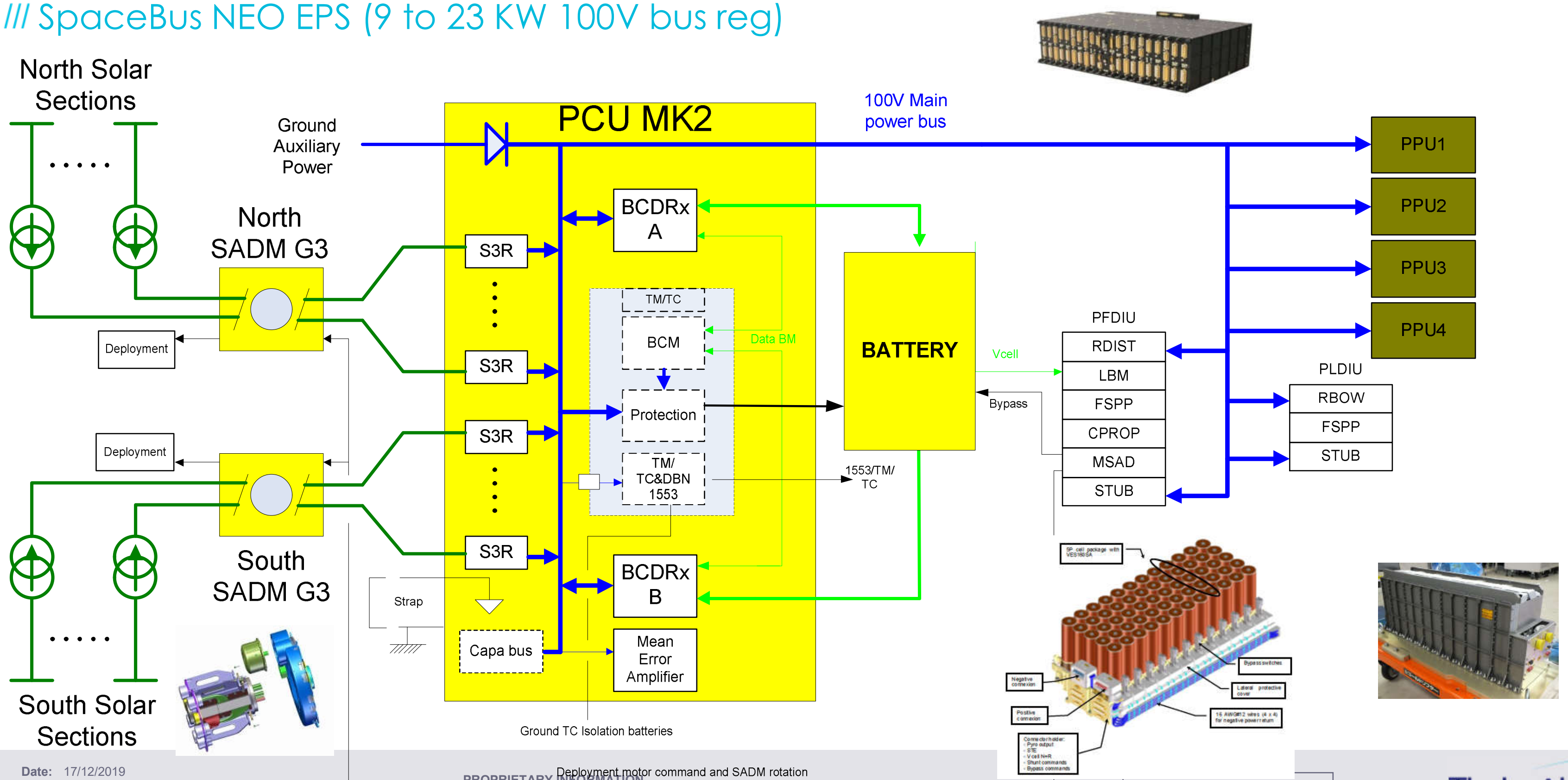
/// Block diagram



-> Operation with primary & secondary power sources whose characteristics are changing with time and conditions of operations

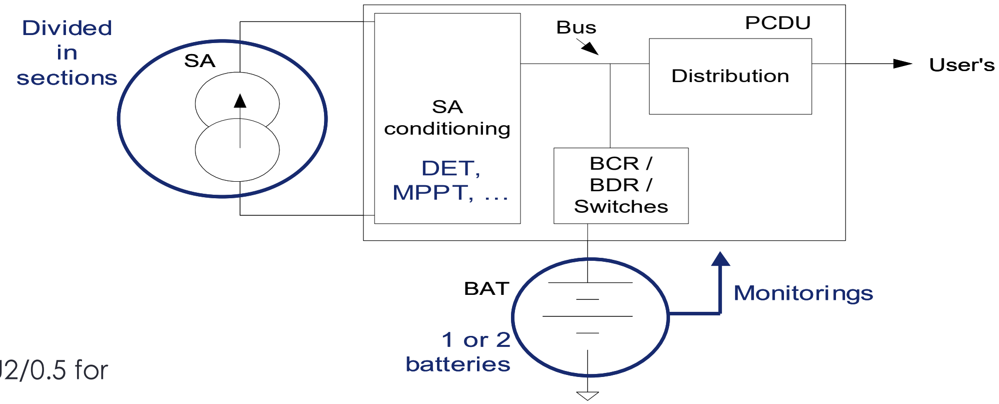
POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// SpaceBus NEO EPS (9 to 23 KW 100V bus reg)



POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Bus voltage selection



/ MANY STANDARDS

- DC: 28V, 50V, 65V, 100V, …
- Even AC busses are used for high power spacecrafts (e.g. ISS)

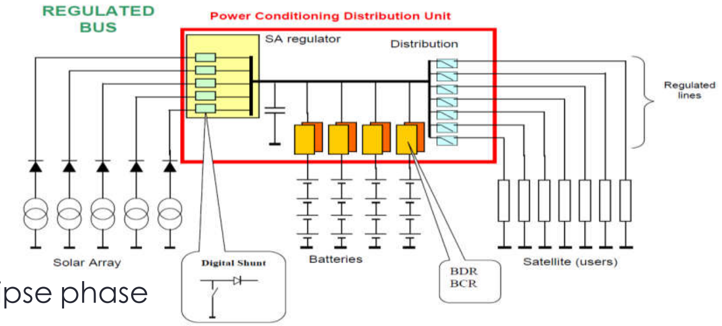
/ CHOICE IS BASED ON

- Bus power
  - Recommended ESA rule: P < U2/0.5 for bus impedance reasons
  - High bus voltage means
    - Less current
    - Simplification of harness
    - « High » voltage management at equipment level (SA, battery, PCDU, …)
- Payload flight heritage

-> SOME ARCHITECTURES MAY EVEN REQUIRES TWO BUSES !!

POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Conditioning architecture

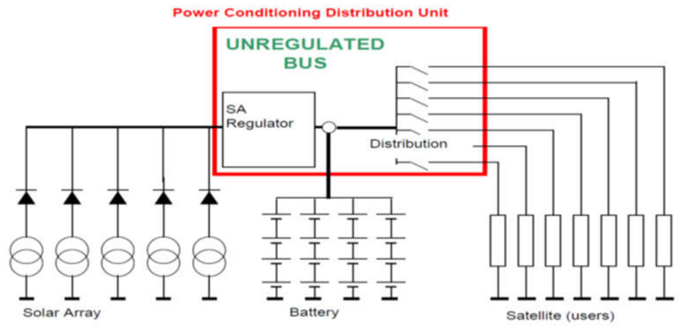


/ REGULATED BUS

- Voltage variation is limited to about +/- 1 V whatever the satellite modes
- Need of dedicated electronics to manage the battery discharge
  - Substantial power dissipation inside the PCDU during eclipse phase

/ UNREGULATED BUS

- Bus voltage is imposed by the battery voltage
  - Impact on all DC/DC converters efficiency



/ SEMI-REGULATED BUS

- Regulated bus in sunlight only

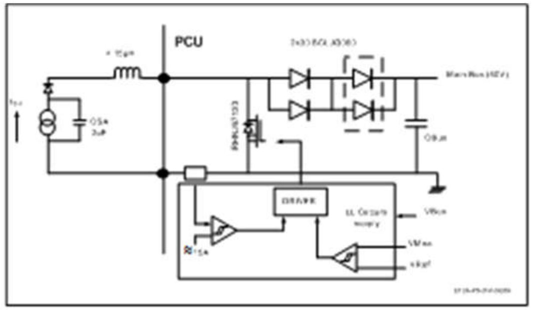
/ CHOICE IS BASED ON

- User's need (mission)
  - Scientific payloads may require regulated bus to fulfill their precisions
  - Thermal stability of some specific loads may requires regulated bus (thermal management is easier in that architecture)
- User's flight heritage

POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Conditioning topology

THE CONDITIONING CONCERNS THE WAY THE POWER COMING FROM THE SOLAR ARRAY IS USED TO BE DELIVERED TO THE DIFFERENT USERS OF THE SPACECRAFT, AS WELL AS TO THE BATTERY IN ORDER TO GUARANTEE THE BATTERY RECHARGE



DIRECT ENERGY TRANSFER (DET)

- DET operates at the bus voltage and extracts the available power from the solar array for this precise voltage
  - Simplest solution

PWM CONTROL OF SA

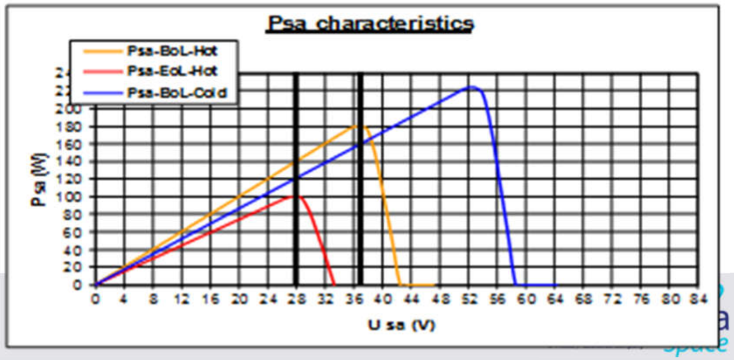
- DC/DC converter implemented between SA and bus

MAXIMUM POWER POINT TRACKING (MPPT)

- MPPT can operate in a wide range of voltages to track the maximum available power from the solar array, converts the (VMP, IMP) into (Vbus, Ibus) and is particularly interesting in case of sensitive flux variations
  - More complex and dissipative solution

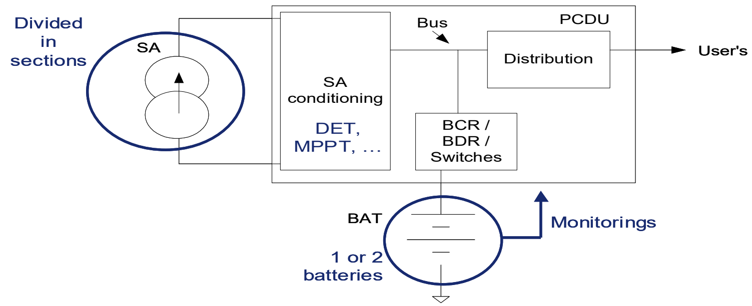
CHOICE IS BASED ON

- Mission & orbit
  - SA flux variation (agility of the S/C, interplanetary missions, …)
  - SA temperature variability
- …



POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Battery management



/ ARCHITECTURE

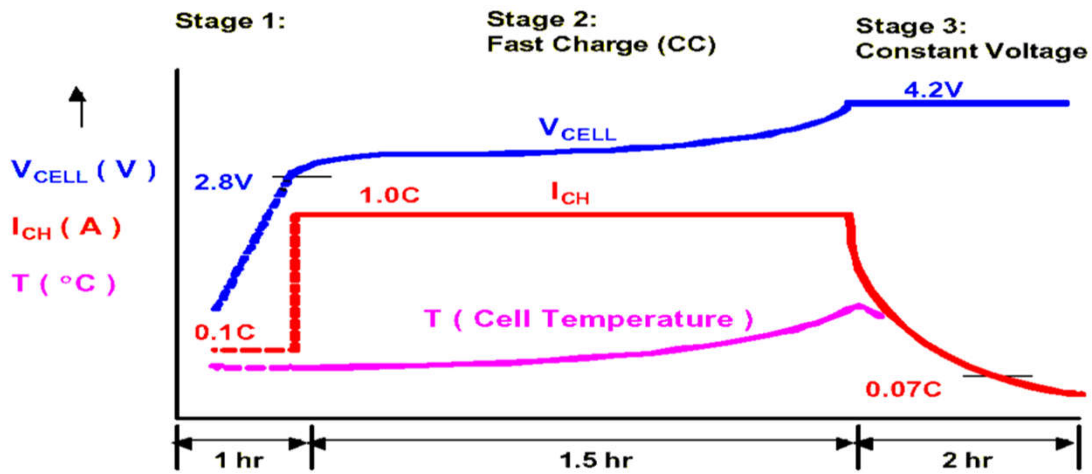
- Centralized
  - Performed by OBC
  - PCDU functions limited to monitoring
- De-centralized at PCDU level
  - Autonomous
    - PCDU ensures battery charge & protections in a reliable way
    - Voltage tapering
    - Protection against over-charge, over-discharge, over-temperature, …
  - Partially autonomous
    - PCDU ensures battery charge & protections
    - OBC is responsible of PCU re-configuration in case of internal failure
- Any intermediate solutions between these two extremes
- Choice based on
  - Price
  - Satellite reliability need
  - …

POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Battery management

/ FUNCTIONS

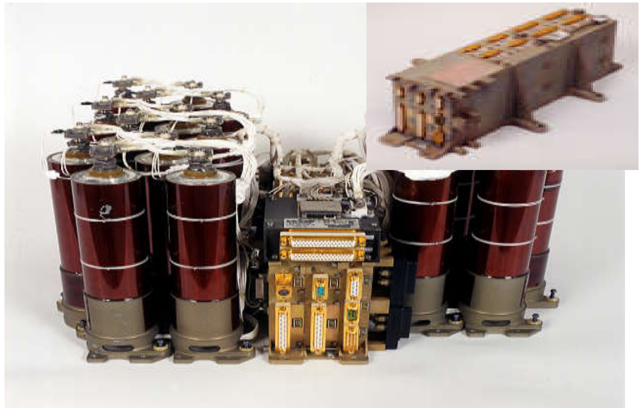
- Voltage / current control during charge
- Current limitation during discharge
- Monitoring
- Protections



POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

///Battery failure modes

- **OPEN CIRCUIT**
  - Loss of battery
- **SHORT FAILURE**
  - Degradation of the voltage



/// Battery protections

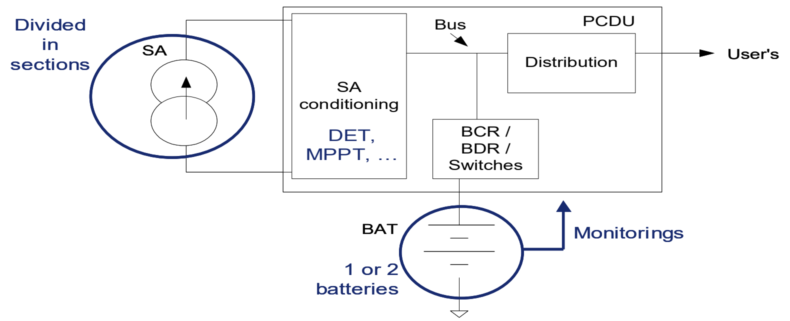
- **BY-PASS**
  - Actuation of electro-mechanical device allowing to short circuit a failed cell and avoid failure propagation at battery level (arm / fire circuitry)
- **BALANCING (LI-ION)**
  - Voltage balancing at cells level via the actuation of a shunt in parallel with the cell to slightly discharge it to improve battery end-of-charge voltage and increase cell life-time
  - Counterbalancing of cells mismatching
- **MAY BE INTEGRATED AT BATTERY LEVEL OR AT AVIONIC LEVEL (PCDU OR NOT)**
- **SOME LI-ION BATTERIES DO NOT NEED CELLS BALANCING THANKS TO BATTERY INNER PROPERTY**

POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

/// Distribution architecture

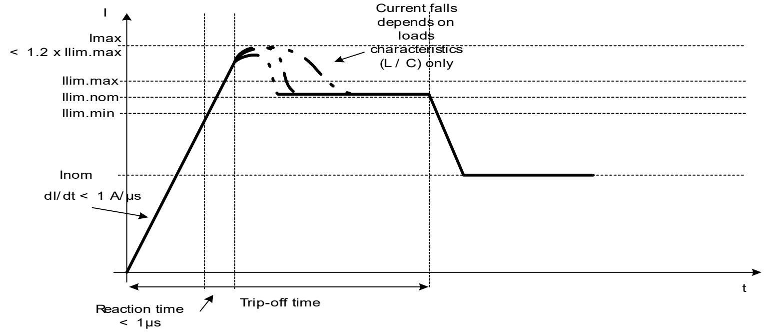
DISTRIBUTION CONCERNS THE WAY THE POWER IS DISTRIBUTED FROM PRIMARY & SECONDARY SOURCES TO USER'S THROUGH PCDU. TO AVOID FAILURE PROPAGATION IN CASE OF USER'S SHORT FAILURE, THESE LINES SHALL BE PROTECTED BY

- **FUSE**
  - Simplest solution
  - Imposes all the user's to be compatible with bus transients induces by fuse blowing
  - Imposes the need of extraction during AIT phase
- **ACTIVE SWITCHES**
  - Flexible solution
  - ON/OFF switching capability
  - Control of fault current

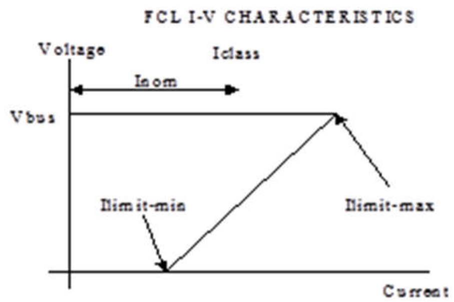


POWER MANAGEMENT, CONTROL & DISTRIBUTION / ARCHITECTURE

///Distribution architecture / some definitions



- **LCL**
  - Latching Current Limiter
  - Limits current at user's switch ON or short failure during limitation time
  - Trips-OFF if limitation time is exceeded
  - ON/OFF command capability
- **FCL**
  - Fold-back current limiter
  - Essential load (e.g. OBC)
  - Limits current at user's switch ON and during short failure (with decreasing level)
- **PO-LCL**
  - Permanent-ON LCL
  - Essential load (e.g. OBC)
  - LCL + automatic periodic re-arming
- **…**



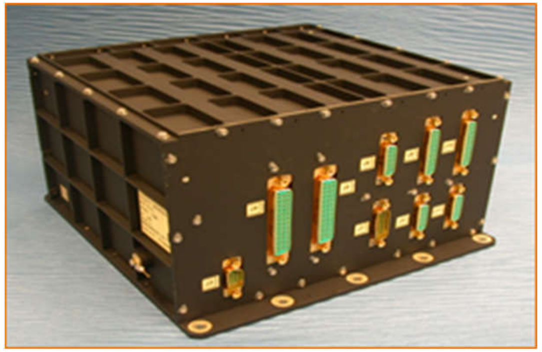
///Other constituents of PCDU

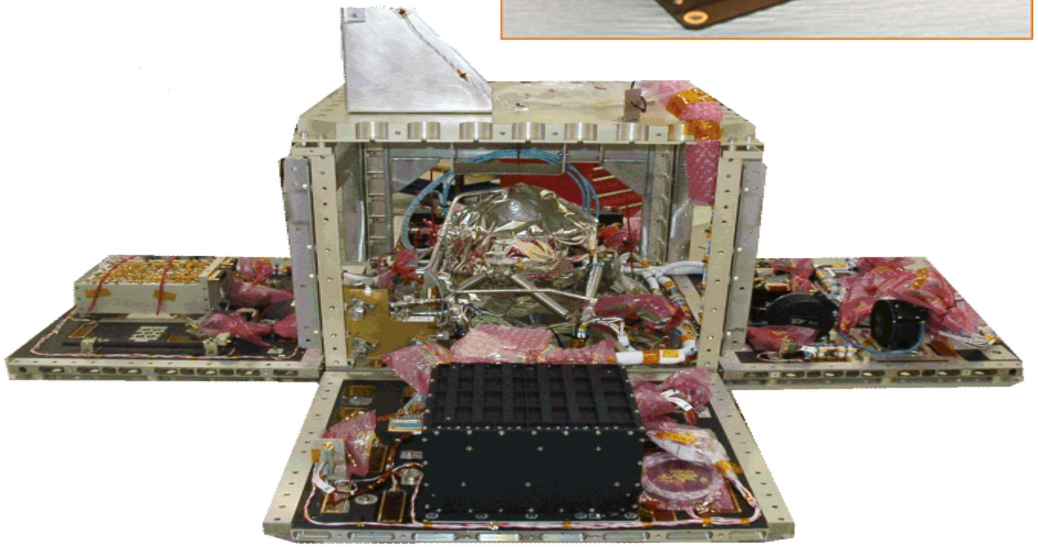
- **COMMAND OF MECHANISMS**
  - SADM motor driver
  - Antenna motor driver
  - …
- **COMMAND ON DEPLOYMENT**
  - Actuation of pyro
  - Actuation of thermal knifes
- **LI-ION BATTERY CELLS MANAGEMENT**
- **ACQUISITION OF THERMISTORS**
- …

POWER MANAGEMENT, CONTROL & DISTRIBUTION / PC(D)U

///Examples µSAT

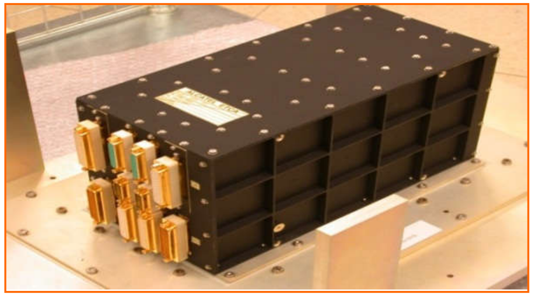
- **LOW POWER: 260 W / LOW VOLTAGE : UNREGULATED BUS (22-37 V)**
- **SOLAR ARRAY REGULATOR: BOOST CONVERTER**
- **NOT RELIABLE**
- **DISTRIBUTION FUNCTIONS**
  - LCL, Pyro
  - DC/DC for secondary (+5, +-15,+20 V) + LCL p
  - Adaptability of the distribution by paralleling
- **CNES/ASTRIUM/TAS-F MYRIADE PLATFORM**





POWER MANAGEMENT, CONTROL & DISTRIBUTION / PC(D)U

///Examples Scientific, earth observation & constellations



- LARGE FLEXIBILITY NEEDED
- MODULAR STRUCTURE
- LARGE FLEXIBILITY
- REDUNDANCY (TOLERANT TO ONE FAILURE)
- BUS POWER : 500 W TO 4200 W
- BUS VOLTAGE : UP TO 50 V, NON-REGULATED OR REGULATED
- SOLAR ARRAY REGULATION : MPPT OR DET (S3R OR S2R)
- LITHIUM CELLS MANAGEMENT : CELLS VOLTAGE BALANCING AND BY-PASS ELECTRONICS
- DISTRIBUTION : LCLS, FCLS, RELAYS+FUSES, HEATER SWITCHES, PYRO ELECTRONICS
- TMTC : MIL-1553B BUS OR OTHER

/// Challenges of new constellations

- USE OF COTS (COMPONENT OFF-THE-SHELF) TAKEN FROM AUTOMOTIVE PRODUCT LINES AND TESTED IN RADIATION "A POSTERIORI" – INCLUDING PLASTIC PACKAGE
- USE OF AUTOMOTIVE PRODUCTION LINES
- REVIEW OF COMPLETE VALIDATION / TEST CONCEPT (BURN-IN AT PART LEVEL, SCREENING AT BOARD LEVEL, LIMITED TESTS AT S/C LEVEL,,,)

POWER MANAGEMENT, CONTROL & DISTRIBUTION / PC(D)U

/// Examples Scientific & earth observation

Illustration CNES

Illustration ESA

POWER MANAGEMENT, CONTROL & DISTRIBUTION / PC(D)U

/// Examples GEO low power

SPACEBUS 3000 PCU

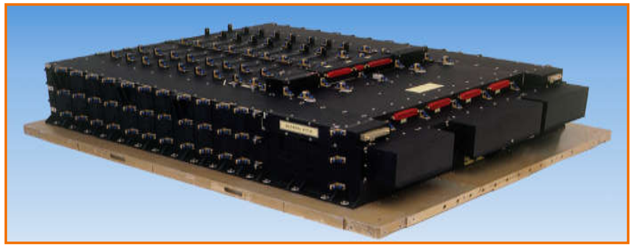
- FULL REGULATED BUS 5.5 KW / 50 V
- SOLAR ARRAY REGULATION: S3R
- NO DISTRIBUTION FUNCTION (PCU ONLY)
- FLIGHT HERITAGE : 35 PCU'S, 380 YEARS

POWER MANAGEMENT, CONTROL & DISTRIBUTION / PC(D)U

/// Examples GEO high power

SPACEBUS 4000 PCU

- **FULL REGULATED BUS 6 TO 27 KW / 100 V**
- **SOLAR ARRAY REGULATION: S3R**
- **NO DISTRIBUTION FUNCTION (PCU ONLY)**
- **FLIGHT HERITAGE : 60 PCU'S, 40 IN FLIGHT, 240 YEARS**



5. POWER BUDGET – PRACTICAL EXERCISE

POWER BUDGET

///Study case

STUDY OF A MICRO SATELLITE TO TARGET SHIP BASED AND GROUND BASED RADARS

- Lifetime: 12 years
- Orbit: Leo

PAYLOAD REQUIREMENTS

- Acquisition in sun & eclipse phases
- Bus power of 650 W
  - Max power to be considered
  - Sum of all user's needs (AOCS, payloads, emitters, receivers, thermal control…) including distribution losses (LCL, fuse, harness)
  - Worst case consumption in all satellite phases (acquisition, data transmission, night& day modes, seasons variation on thermal control, …)
  - Excluding power conditioning needs

POWER BUDGET

///Orbit selection

ALTITUDE TRADE-OFF

- Lower than 1000 km (to avoid Van Allen belts impacts on radiation level
- Above 500 km to ensure that the cluster altitude can be maintained during lifetime (atmospheric drag effect)
- Instrument precision is better at low altitude but instrument coverage increases with altitude

-> Circular orbit of 600 km altitude has been selected among several candidates (out of the scope of this study case, based essentially on payload needs)

INCLINATION TRADE -OFF

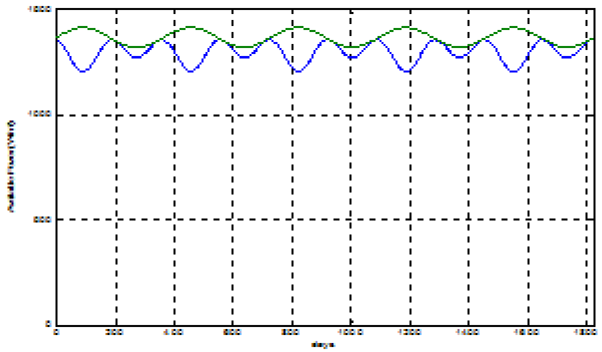
- Polar orbit for best possible coverage worldwide
- Sun-synchronous orbit as other candidate

Orbit characteristics		
Average height	600 km	600 km
Period	97 min	97 min
Eccentricity	0.001 (circular orbit)	0.001 (circular orbit)
Inclination	90 ° (polar orbit)	98 ° (sun-synchronous)
Eclipse duration	21.3 min	30 min

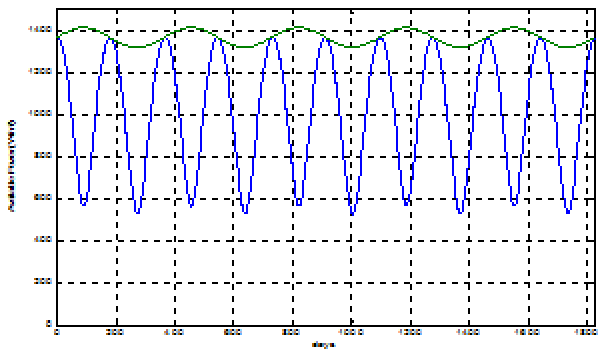
POWER BUDGET

/// Orbit selection / Inclination trade-off

Orbit selection / Inclination trade-off



SA flux (sun-synchronous orbit)
-> Min SA flux = 1220 W



SA flux (polar orbit)
-> Min SA flux = 520 W

POWER BUDGET

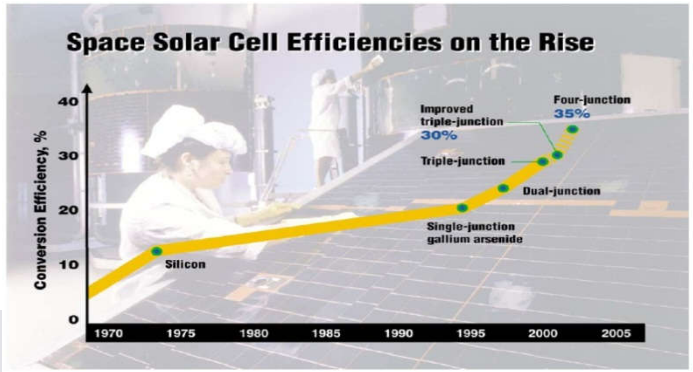
///Orbit selection / Inclination trade-off

- **EPS SIZING SHALL CONSIDER WORST CASE CONDITIONS OF ILLUMINATION AND EOL PHOTOVOLTAIC EFFICIENCY OF SA CELLS. THIS LEADS TO THE FOLLOWING DATA (WORST CASE FIGURES).**

	Sun-synchronous	Polar
Minimum SA flux (W/m²)	1220	520
BOL SA cell efficiency	28 %	
EOL/BOL ratio	76.5 %	
Total available SA power (W / m²)	260	110

Cell manufacturer data

- **NOTE THAT PHOTOVOLTAIC EFFICIENCY EOL/BOL RATIO TAKES INTO ACCOUNT THE FOLLOWING ELEMENTS (SA PANEL MANUFACTURER DATA)**
  - 5-years mission lifetime
  - radiation effects
  - UV and meteoritic impact
  - effect of ATOX density (aggressive and corrosive environment tied to the LEO) on cover glass protection
  - Effect of temperature (including earth albedo)



POWER BUDGET

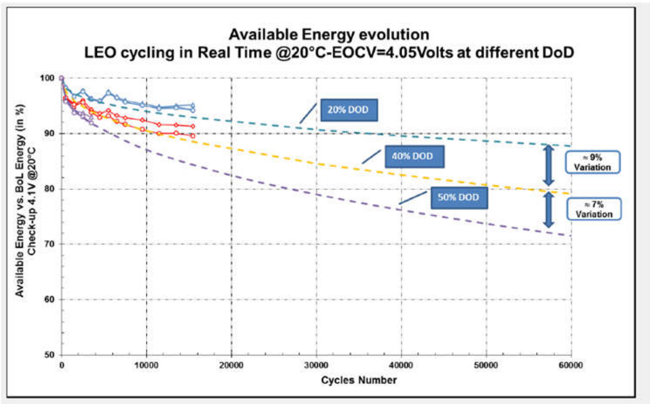
/// EPS sizing / bus voltage trade-off

- **28 V**
  - Compatible with bus power (< 1 kW)
  - High hardware heritage
- **50 V**
  - Reduced current levels
  - Reduced harness & power dissipations

/// EPS siring / Battery sizing & bus regulation trade-off

- **REGULATED POWER BUS – MAIN HYPOTHESIS**
  - BDR (Battery => bus) conversion efficiency — 94%
- **UNREGULATED POWER BUS – MAIN HYPOTHESIS**
  - Internal losses (Battery => bus) internal connections — 1%
- **BATTERY**
  - Max DOD of 40 % considered following
    - Orbit characteristics (period and eclipse)
    - Mission duration 10 years => 55 000 cycles
  - Battery dissipation (at battery level)
    - 25 W (discharge)
    - 15 W (charge)
  - BAT to PCDU harness losses : 3%

NOTE: PCDU LOW LEVEL CONSUMPTION: 30 W FOR BOTH CONFIGURATIONS



POWER BUDGET

/// EPS sizing / bus regulation trade-off & Battery sizing

	Regulated bus	Unregulated bus
User's power in eclipse (W)	650	
PCDU losses during eclipse (W)	70	35
Satellite power requirement in eclipse (W)	720	685
Harness & Battery losses (W)	50	45
Total battery power need in eclipse (W)	**770**	**730**
Eclipse duration (min)	30	
Battery useful cycled energy requirement EOL (W h)	385	365
Battery energy mission degradation (40% DoD / 56000 cycles)	30 %	
Battery useful cycled energy requirement BOL (W h)	550	520
Battery energy requirement BOL (Wh)	1375	1300

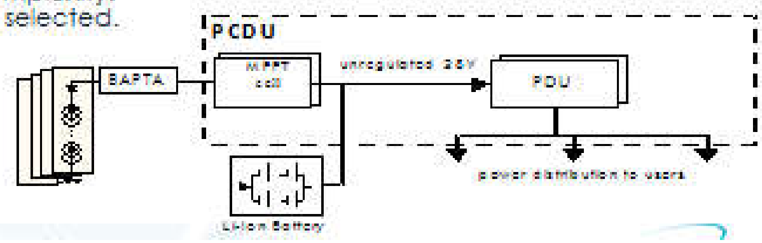
Pout/n – Pout + LL

Pecl*0,5 h

20% fading
5% calendar loss
5% Rbat degradation

Energy/DOD

Slight advantage for URB coupled with lower PCDU mass / complexity.
If no specific requirement on payload (including EMC), URB is selected.



POWER BUDGET

///EPS sizing / Conditioning topology trade-off

UNREGULATED TOPOLOGY

- Internal PCU losses (Battery => bus): 1%
- PCDU low level consumption: 30 W for both configurations

MPPT

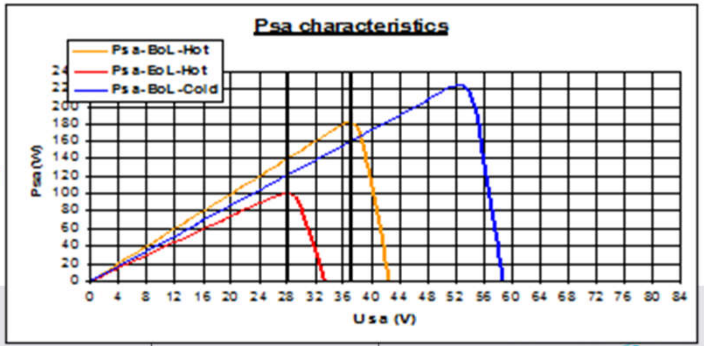
- Conversion efficiency: 95 %
- Ability to track the maximum power whatever the battery state is (charged, discharged, with or without failure, …): 99 % accuracy

DET

- Conversion efficiency: 98 %
- Since DET extracts SA power at fixed battery voltage [28 V; 37 V], SA electrical efficiency is never perfectly optimized, leading to a mean value 5 % lower than maximum value (typical value, function of SA sizing/temperature & battery EOC, / failure modes)

BATTERY DATA (BASED ON PREVIOUS SELECTION)

- Battery recharge duration = 90 % of sunlight duration



NOTE: CONSIDERING 28 V URB WITH 40 % DOD, BATTERY VOLTAGE IS COMPRISED BETWEEN 28 & 37 V IN NOMINAL OPERATING CASES

POWER BUDGET

/// EPS sizing / Conditioning topology trade-off

	MPPT	DET
Battery power requirement in eclipse (W)	730	
Eclipse duration (min) / Battery charge duration (min)	30 / 60	
Battery charge power need (W)	365	
Harness, BAT & PCDU losses (W)	30	
Battery recharge power need (W)	**395**	
User's power need in sunlight (W)	650	
Battery recharge power need (W)	395	
PCDU low level (W)	30	
Total bus power needs (W)	**1075**	
SA conditioning losses (W)	70	20
TOTAL SA power needs (W)	1145	1095
SA efficiency (W/m²)	261	248
Minimum SA surface requirement (m²)	4,4	4,4

(97 -30)*0.9

((Pecl)*30 min)/T_{charge}

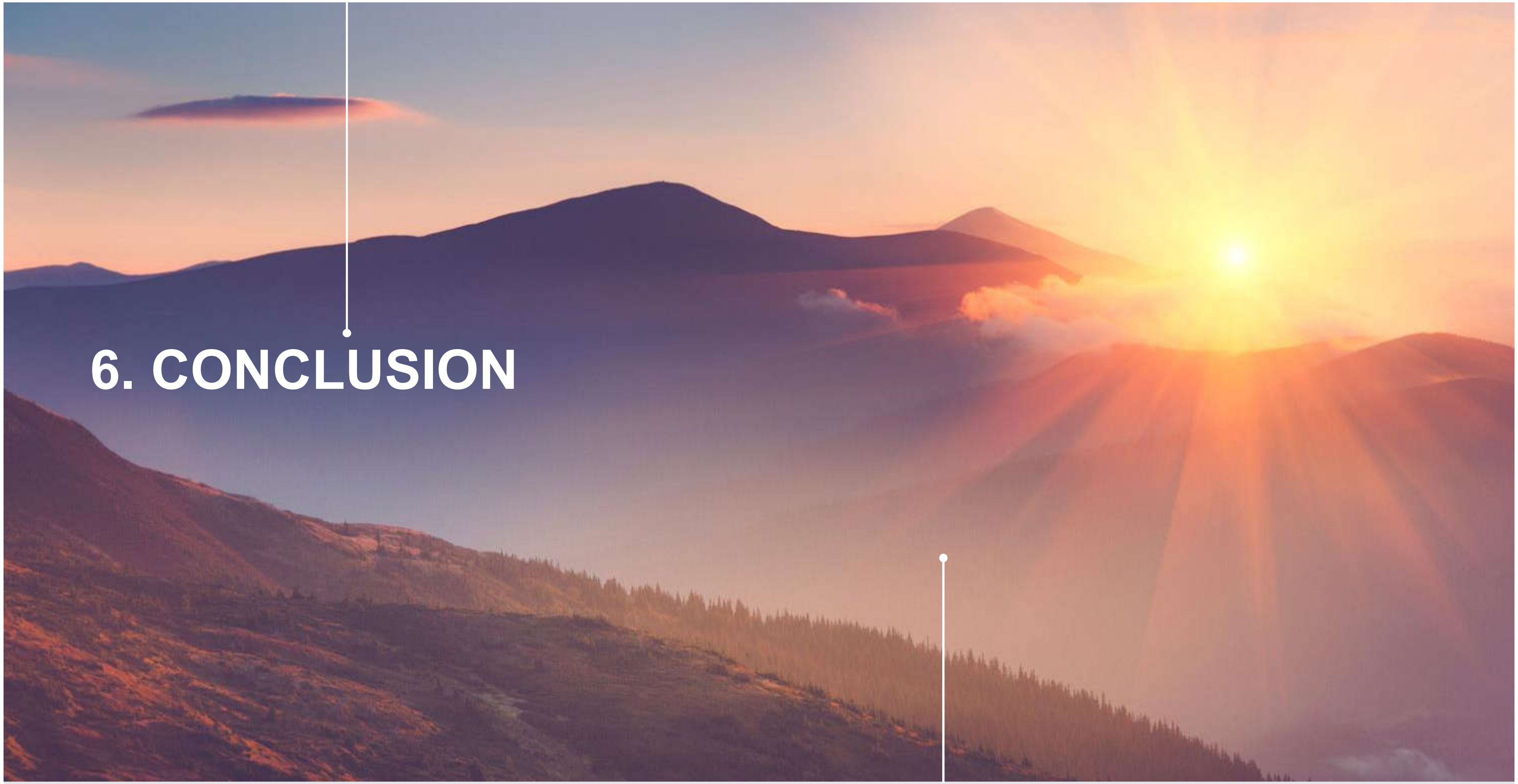
1% PCDU; 3% harness; 15W BAT

5 % MPPT & 1% tracking vs. 2 % DET

Non-optimization : 5%

No impact on SA size (considering nominal / constant SA illumination)

	Sun-synchronous	Polar
Minimum SA flux (W/m²)	1220	520
BOL SA cell efficiency	28 %	
EOL/BOL ratio	76.5 %	
Total available SA power (W / m²)	261	111



6. CONCLUSION

CONCLUSIONS

/// The design of any Power Subsystem is strongly linked with System analyses (Attitude & Orbit, Mission, Operations)

/// The electrical architecture of spacecrafts is not standard

- **UNREGULATED OR REGULATED POWER BUS**
- **VOLTAGE (28 V, 50 V, 100 V, …)**
- **CONDITIONING (S3R, MPPT, …)**
- **PROTECTIONS (RELIABLE OR NOT)**
- **DISTRIBUTION (FUSE, LCL, …)**
- **…**

MMRTG Engineering Unit

AND SHALL BE ADAPTED NEARLY ON CASE BY CASE ….

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MMRTG Engineering Unit


THANK YOU
FOR YOUR ATTENTION