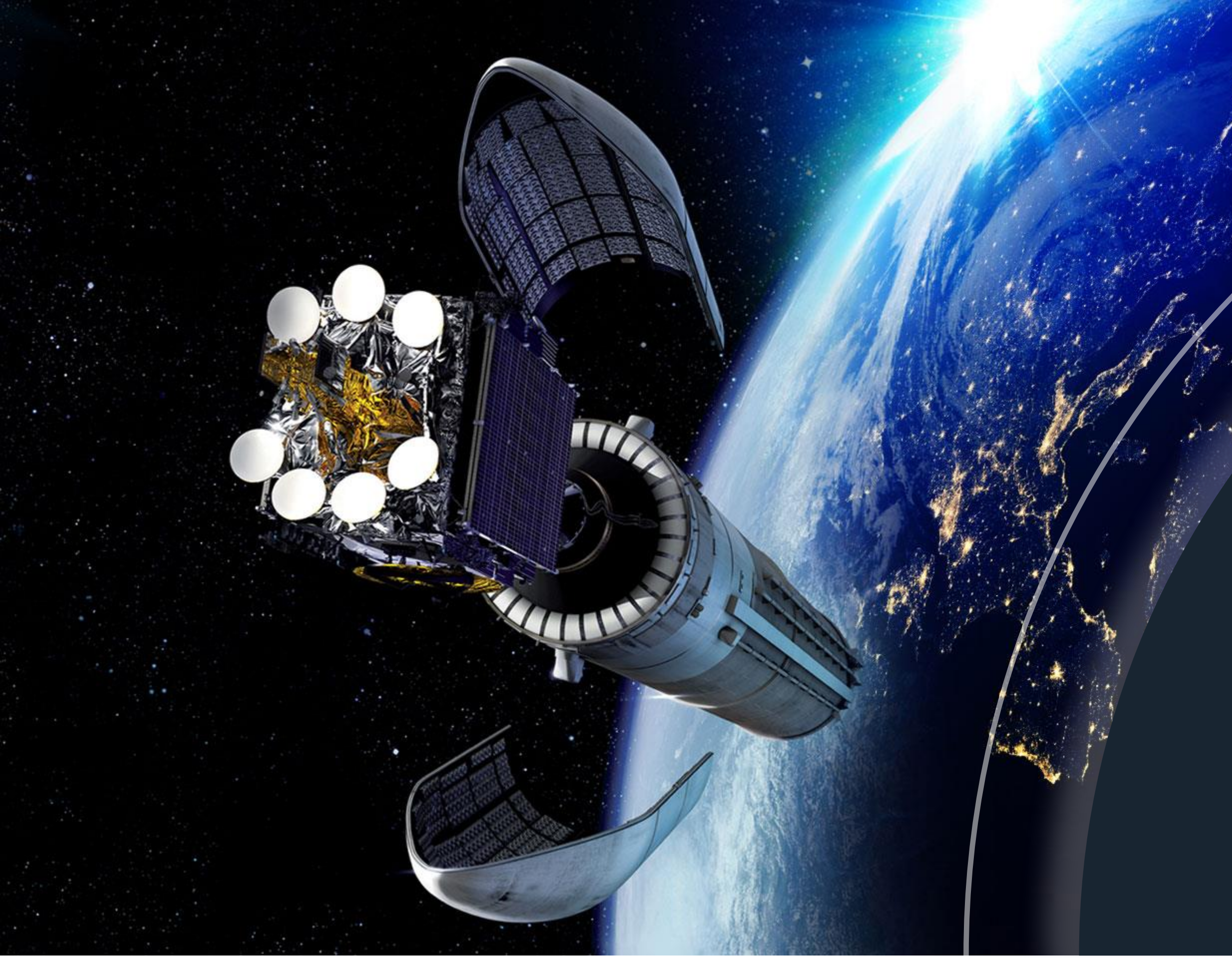
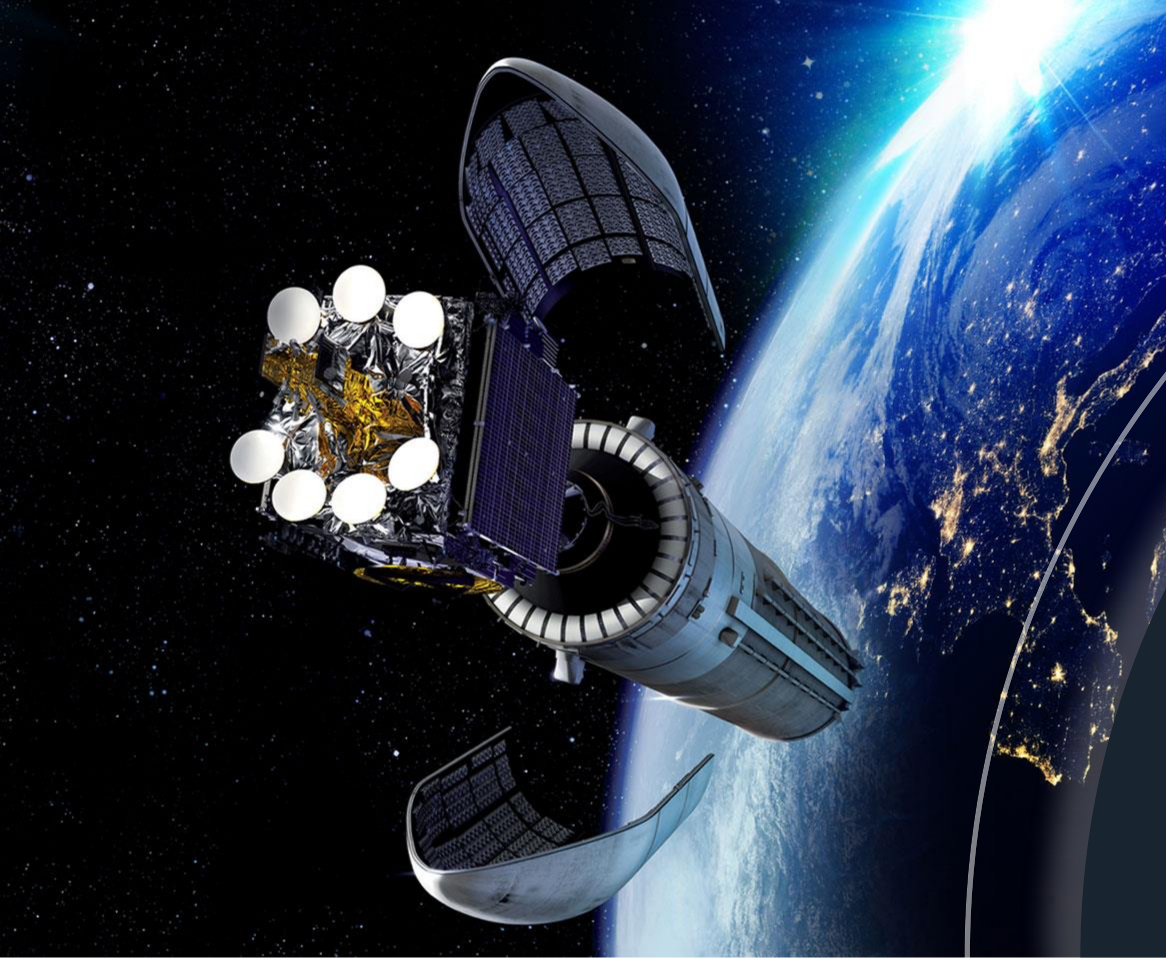


Electrical Power Systems

Vincent Lempereur

Agenda

1. **Introduction**
   - Presentation of Thales Alenia Space Belgium (ETCA)
   - Presentation of myself
   - EPS – general information
2. Primary power sources
   - Solar cells & solar arrays
   - Fuel cells
   - RTG
   - Others
3. Secondary power sources - batteries
4. Power Management, Control & Distribution
   - Architecture
   - PCU / PCDU
5. Power budget – practical exercise
6. Conclusions



Thales Alenia Space

In BELGIUM

ThalesAlenia Space
a Thales / Leonardo company

CONTENTS

THALES

The Thales group

Corporate presentation

OPEN

Thales group

Employees
64 000

Global presence
56 countries

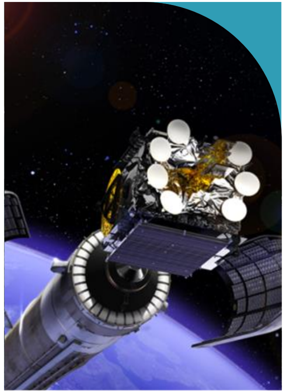
Self-funded R&D* 2016
731 million euros
* Does not include therefore R&D undertaken with external funding.

Revenues in 2016
15 billion euros

A balanced revenue structure

Defence	Civil
50 %	50 %

AEROSPACE



SPACE

GROUND TRANSPORTATION

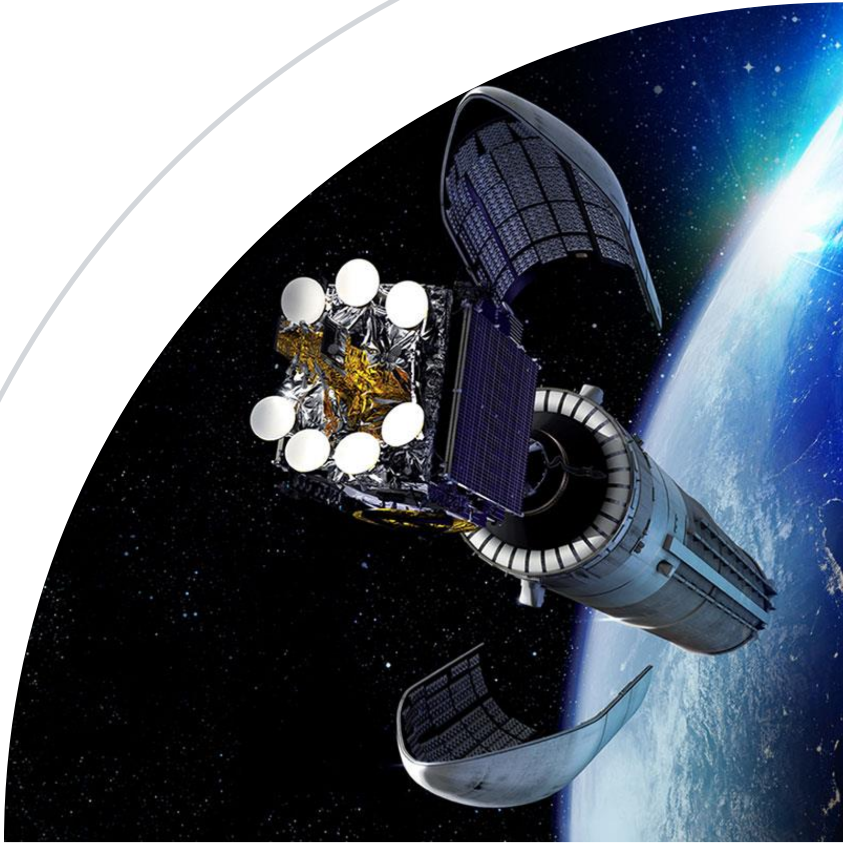
DEFENCE

SECURITY

TRUSTED PARTNER FOR A SAFER WORLD

Thales Alenia Space

We bring a new dimension to your horizons

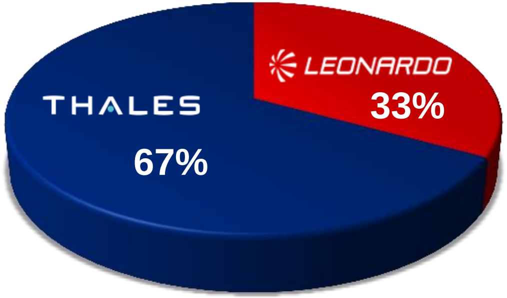


Thales Alenia Space

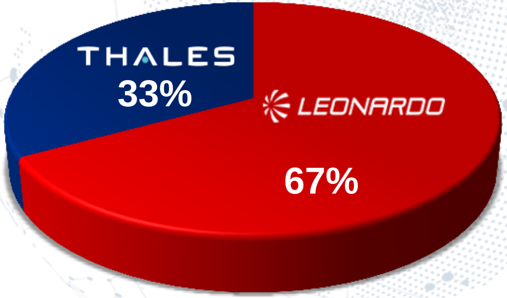
A JOINT VENTURE BETWEEN TWO LEADERS

A UNIQUE COMBINATION OF EXPERTISE COVERING THE FULL VALUE CHAIN

ThalesAlenia Space
a Thales / Leonardo company



TELESPAZIO
a LEONARDO and THALES company



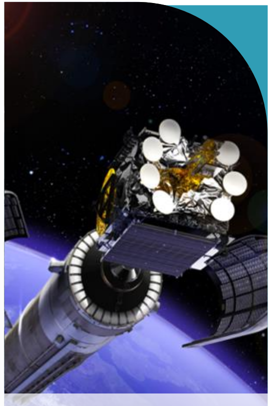
SPACEALLIANCE

Thales Alenia Space

A global player in all fields of Space

A global offer from equipment to end-to-end space systems.

We ensure the end-to-end design, manufacture and delivery of space systems



TELECOM

Fix phones / Cell phones
Broadband
Dual / Military
Secure lines

OBSERVATION

Climate change
Meteorology
Oceanography
Intelligence
Surveillance

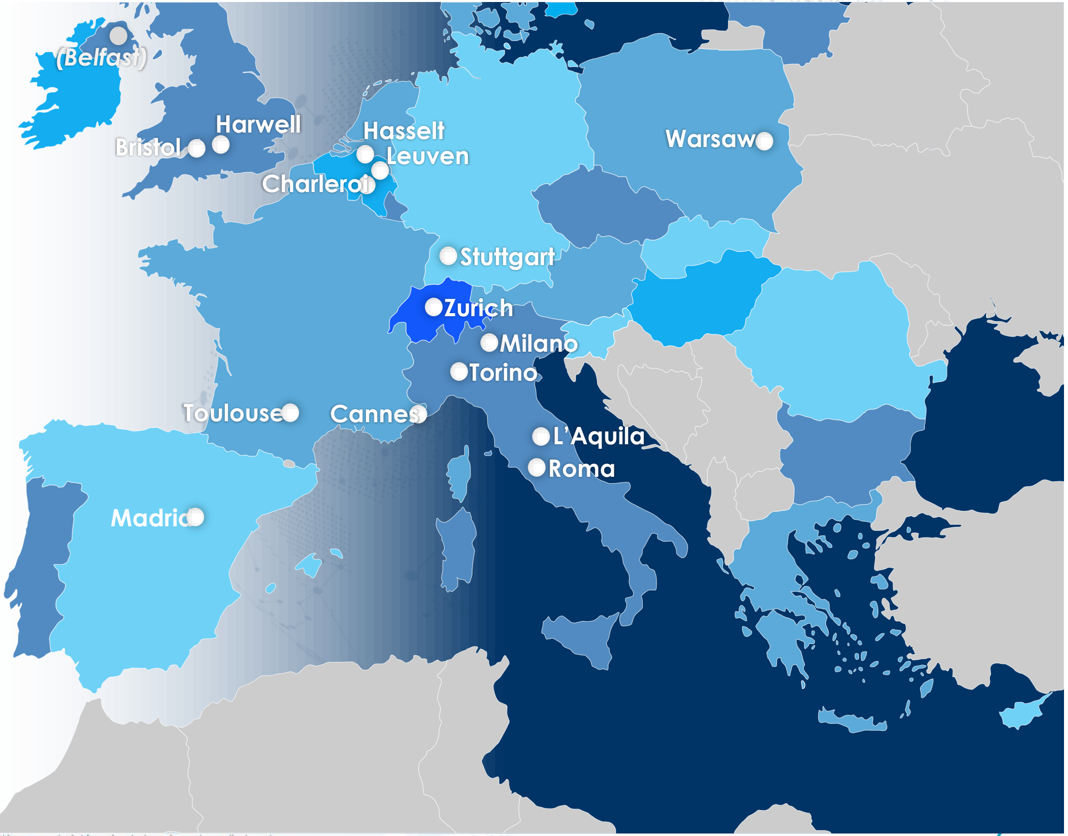
NAVIGATION

Localisation
Aeronautical communications
Data gathering

EXPLORATION SCIENCES

Planetology
Fundamental physics
Astronomy
Human spaceflight
Space Transport System

A global industrial presence in Europe



7980 employees

9 countries

2,4 billion € sales in 2016.

ThalesAlenia Space
a Thales / Leonardo company

Serving our clients all over the world

Globalstar
Intelsat
Iridium
JPL
NASA
SES Americom
Sirius Radio
XM Satellite Radio
Worldspace

Arsat
Nahuelsat
Star One
Visiona

Asecna
Globacom
Rascom
Vodacom

ASI
CNES
French MoD
DLR
ESA
Eumetsat
European commission
Eutelsat

France Telecom
Italian MoD
Hispasat
Inmarsat
O3b networks
SES
Telenor
Turksat

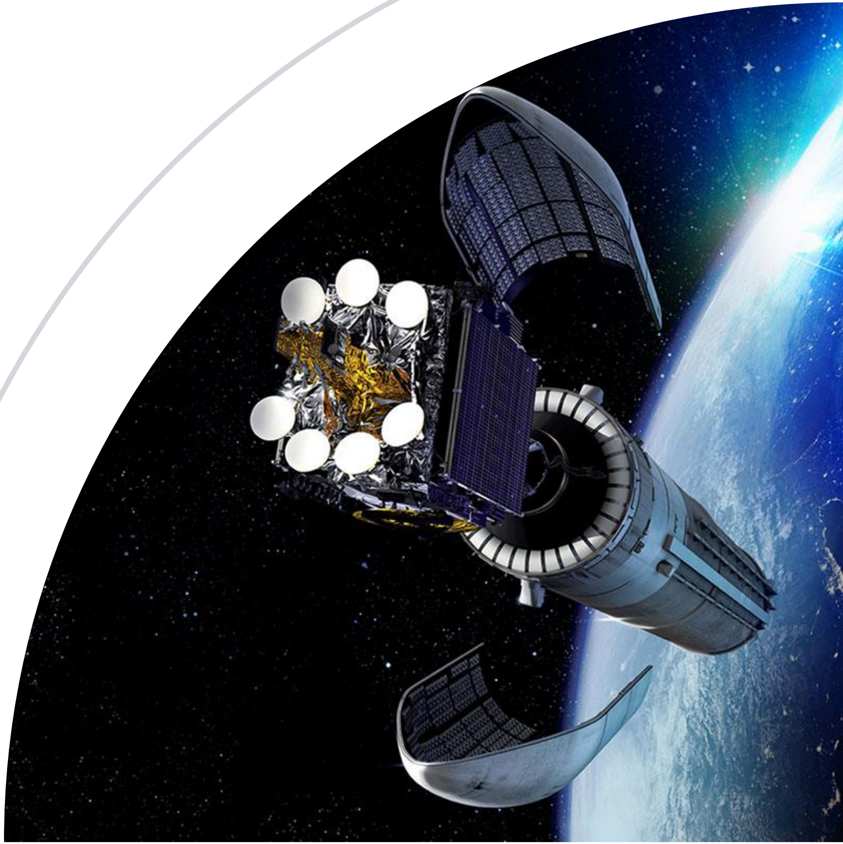
Arabsat
IAI
Nilesat
Spacecom
Yahsat

ISRO

Turkmenistan
Gascom
JSC "ISS"
Krunitchev
RSCC
RKK Energia
Gazprom

Mitsubishi
NEC/Toshiba
APT
ADD
CASC/CAST
Chinasat
Indosat
KT
ShinSat
Sinosat
Telkom
KARI

Thales Alenia Space in Belgium



Thales Alenia Space in Belgium
3 facilities

CHARLEROI

- **Development, Manufacturing and Marketing of electronic products and software**
- **for satellite market**
  - Telecommunication ;
  - Defense ;
  - Observation ;
  - Exploration ;
  - Navigation ;
  - Science
- **for European launchers** (Ariane, Soyuz and Vega)
- 35 000 sq
- Clean rooms : 6 550 sq

LEUVEN

- **Microelectronic solution**
- **Avionic electronic products and software**
- **Opened since June 2014**
- 400 sq

HASSELT

- **Automated manufacturing of photovoltaic assemblies (PVA)**
- **Industry 4.0**
- **Smart data**
- **Opening and start of production: Q2 2018**
- 2000 sq

Thales Alenia Space in Belgium

Expertise and Business

Thales Alenia Space Belgium is one of the key Electronics Competence Centers of Thales Alenia Space

We develop and product equipment dedicated to Thales Alenia Space's satellites and also to the Export Market.

With the new facilities in Flanders,

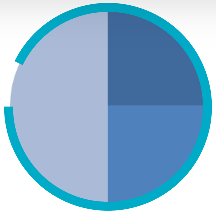
- we strengthen our European footprint
- we increase our portfolio of products
- we intensify synergies with research centers and universities

New: QUALIF of DPC

Thales Alenia Space in Belgium
Some key numbers

Over 700 collaborators with varied employment profiles, experience and expertise

+40%
over the last three years



- Workers
- Employees
- Engineers & managers

3.2
million € training effort in 2016

Revenues

+50%
over the last three years

70%
satellites

30%
Launchers

Products

Satellite Platform

A World leader in Electrical Power Conditioning and Distribution

PCU (Power Conditioning Unit)
transforms energy received from solar panels and batteries into the appropriate power for the various items of satellite equipment.

PCDU (Power Conditioning & Distribution Unit)
also carries out distribution and avionic functions.

A complete range of equipment :
LEO - MEO - GEO

PCU : 50 FMs sold for 10 years
(TAS, OHB, Russia, Asia, Argentina, ...)

PCDU : 160 FMs sold
(Iridium, O3B, Globalstar, Galileo, Copernicus, ...),

European leader in Power Supply for Electrical Propulsion

PPU MK1 and MK2 (Power Processing Unit)
Station keeping and supply for electrical thrusters (2,5 kW).

PPU MK3 (New product qualified in 2016)
also takes care of orbit rising and deorbiting.
PPU MK3 will supply thrusters of up to 5 kW.

PPU MK1 et MK2
Some 50 units ordered by Airbus DS (EUR3000), Thales Alenia Space (SB4000), OHB (SGeo), IAI, ISS, ...

PPU MK3
19 FMs ordered
Compatible with Russian (Fakel) et European (SNECMA) motors

Products
Satellite Payload

Key player in Electrical Power Conditioner for Travelling Wave Tube Amplifiers

TWTA (Traveling Wave Tube Amplifier)

These equipment re-transmit television and telecommunication signals, meteorological images, data of scientific mission…

Available in « Single » and « Dual » version.

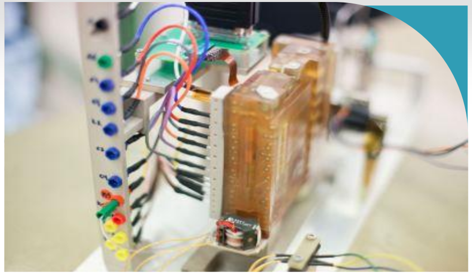
Our strengths: power and frequency range flexibility coupled with flight quality

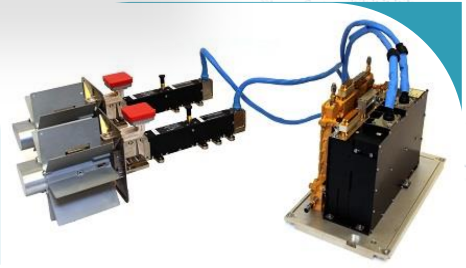
More than 1000 FMs ordered (MTG, EXOMARS, Sentinel, Pleiades, Koreasa, Chinasat, Gokturk, Solar-Stereo, Turkmensat, Eutelsat 8WB, SGDC, Rosetta…)

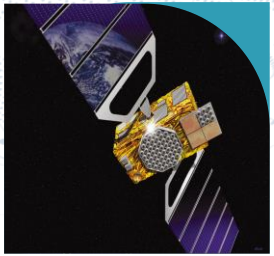
More than 50. 000.000 hrs. of orbital experience

The LC-TWTA DUAL FLEX:

Beyond its basic mode, 2 TWTs supply this equipment allows the on-board computer to adapt the TWT operating point in both power output and frequency range.







Other Products

Satellite

Avionics : Technological Breakthrough Equipment

Functions:
- **Motor Drive Electronics** (for solar arrays, antenna, thrusters, ...)
- **Avionics** (power distribution, pyro controls, heaters, battery management, ...)

Products:
- **SDIU** (Standard Distribution & Interface Unit) for GEO satellites (Neosat).
- **RTU** (Remote Terminal Unit) for LEO and MEO satellites
- **SADE, DCU, ...** for LEO and MEO satellites

Innovation: It can include a digital programmable controller (DPC), hybrid ASIC (digital and analog).

References : Exomars 2020, Amos 4, Yamal 401, Swim, Sicral 2, Koreasat 7, Eutelsat 8 WB, Yamal 601, Turkmenalem, ...

Specialist in DC / DC converters

- **LPLC (Low Power Low Cost)**
  - Hybrid technology
  - Production of 250 flight models per year
- **Specific Power Supply**
  - Pulsed Power Supply for radars and altimeters

16/11/2017
Ref.: VLR/080066_0900
Ref. Model = 83230347-DOC-TAS-EN-005

Products

Satellite PVA

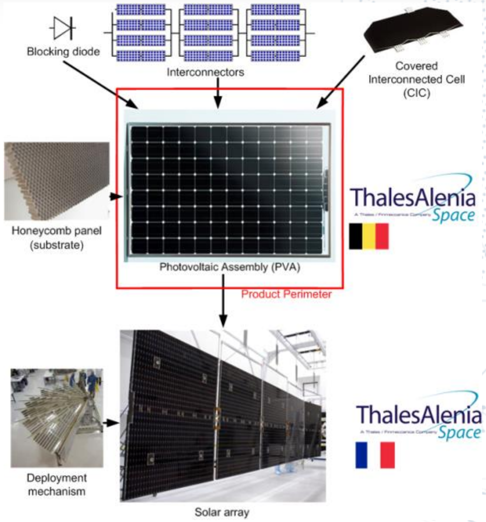
The company makes its mark on Industry 4.0 and smart data

PVA PROJECT INCLUDES :

- design & set-up of in-house production line
- Development of PVA product line for a better fit with solar array product policy

STRATEGIC STAKES FOR TAS :

- Reduce recurring cost for PVA through:
  - ✓ disruptive approach on assembly process with automatisation, adapted to space domain
  - ✓ reduction of interfaced suppliers (5+) in supply chain
- Win access to mega-constellations market



Robotized assembly of the panel

Digital management of data and traceability

Tests and checks on the production line

Introduction of augmented reality

Relevant and fast smart data analysis from all sources

Products

A Key player for European launchers : Ariane, Soyuz and Vega

Leader in on-board electronics for Ariane 5

Main supplier for Ariane 5

Development and production of the launcher's control & command Benches

23 devices and modules per launcher

5, 6 to 7 launches per year

The Ariane Adventure continues

Participation in the development of the safeguard system

Participation in the development of Thrust Vector Activation Systems

The first flight of Ariane 6 is expected in 2020

Sole non-Russian supplier for the Soyuz (Kourou)

Exclusive supplier of the Soyuz safeguard chain

- 1 complete system per launcher
- 2 to 4 launches per year since 2011

SRP (Passive Repeater System) enabling communication between the payload and ground control systems prior to launch

Innovation

from micro component to satellite architecture

A dedicated team
- A team of 15 people is dedicated to innovation
- Mix of seniors experts and juniors engineers

An Open Innovation
- Collaboration with Universities, labs and SME

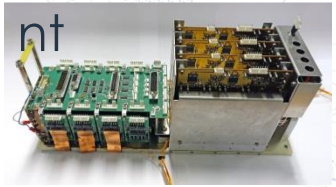
UCL ULB UMONS Université de Mons imec EURO HEAT PIPES sonaca BELGIUM sirris

- Strong link with other TAS entities

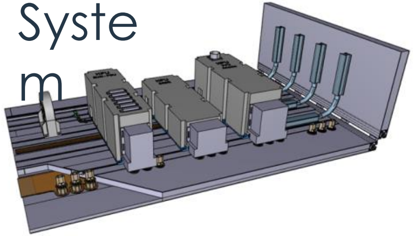
A large panel of various research topics
- Micro electronics
- New Power Architecture
- Thermal Management at equipment level
- Optical technologies
- High voltage technologies

sonaca ThalesAlenia a Thales / Leonardo company Space UMONS Université de Mons jdc sirris

Equipement



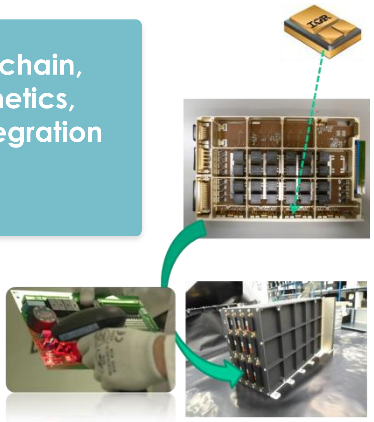
System



A strong and efficient industrial base

Permanent & continuous improvement, with LEAN, to reach Industry 4.0 state of the art

A complete supply chain, from hybrids, magnetics, PCBA to products integration & test



High level set of production and test means

Electrodynamic Shaker

Thermal vacuum - test chamber

Pyroshock test facility

EMC tests chamber

Introduction / V. Lempereur

Training

- Electrical / Electronic engineer from ULG (1996)

Professional career in TAS-Belgium

- Designer on PCU /PCDU
  - SB4000 SUN & PCU, PLEIADES
- TAS-B's resident in Cannes during two years (EPS architecture / PCDU phase A / …)
  - Wales / Earthcare / Spectra / Exomars / Galileo / Pleiades / …
- Technical manager on PLEIADES DRU (PCDU)
- Project manager on PCDU / PSU projects
  - SIRAL PSU, ALTIKA, MIRI
  - µSAT PCDU
- PCDU/PCU product manager
- TAS-B's resident in Cannes during three years (EPS architecture / PCDU phase A / …)
- PCDU/PCU & EPS product manager

© CNES - Mars 2003 / illustration Pierre CARRIL

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

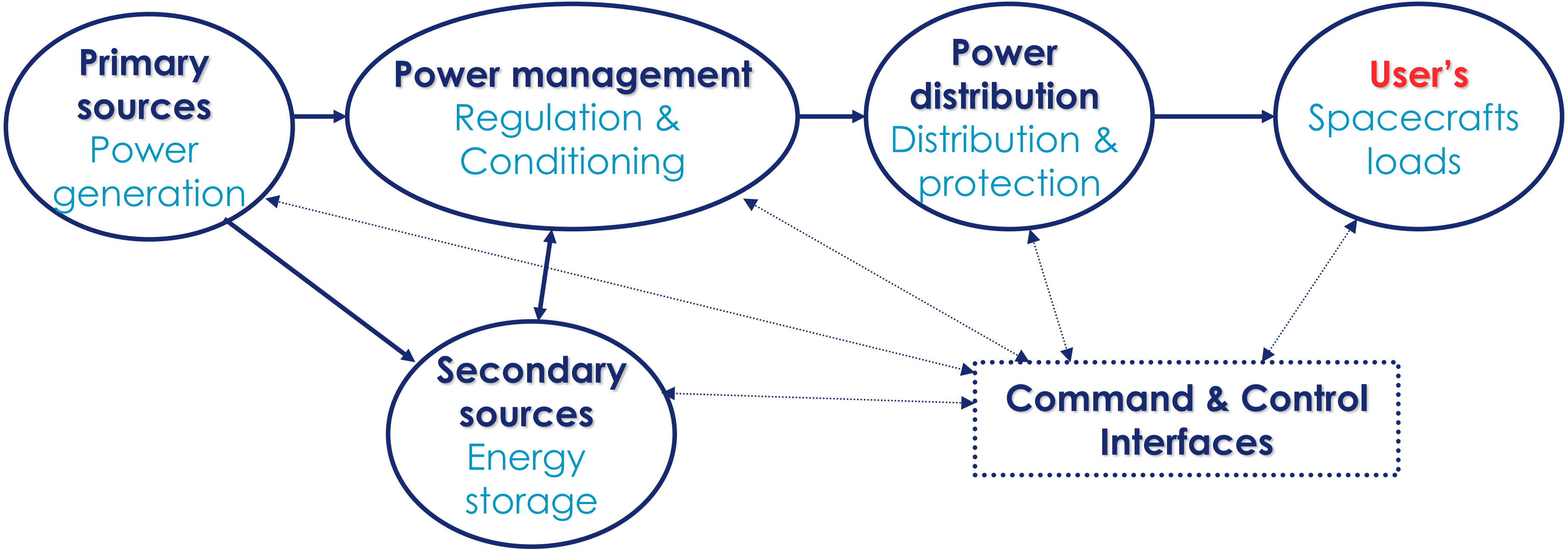
Satellite Electrical Power Subsystem (EPS) shall

- 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)

Note: power system failure means the loss of mission

Introduction / EPS general information

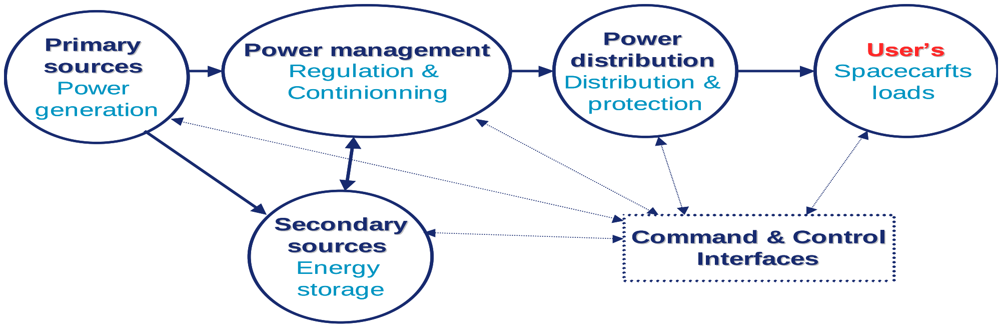
General functional block diagram



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 a 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

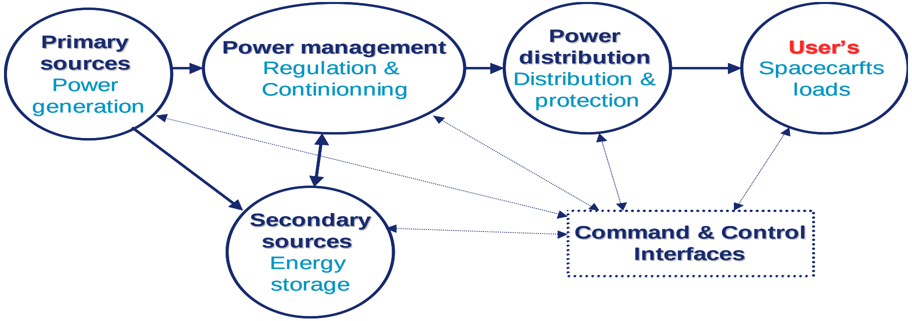


Introduction / EPS general information

Functions (2)

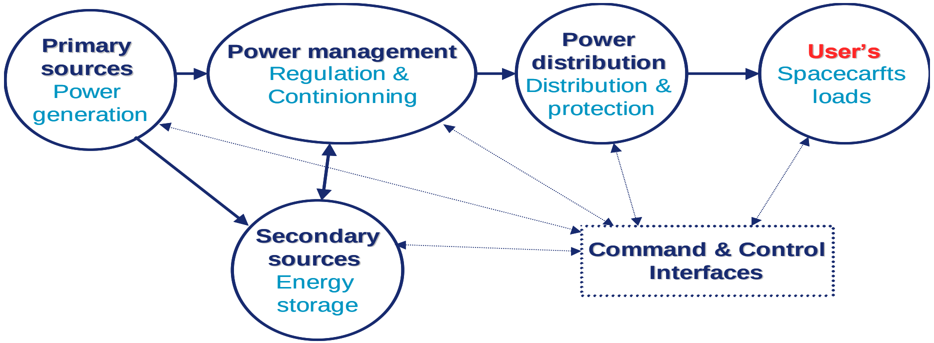
- Conditioning and regulation
  - This function covers everything which is required to adapt the primary sources to the need of users 'equipment'
  - Regulators
    - To maintain a constant voltage or current
    - Regulation of battery charge and discharge, regulation of the commutation of solar generator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

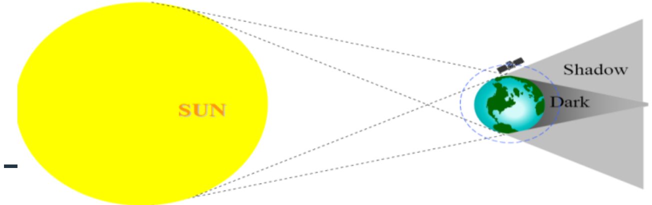
- Low Earth Orbit (LEO), geostationary (GEO), Mean Earth Orbit (MEO), Sun Synchronous Orbit (SSO), Sun Centric (Interplanetary), …

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

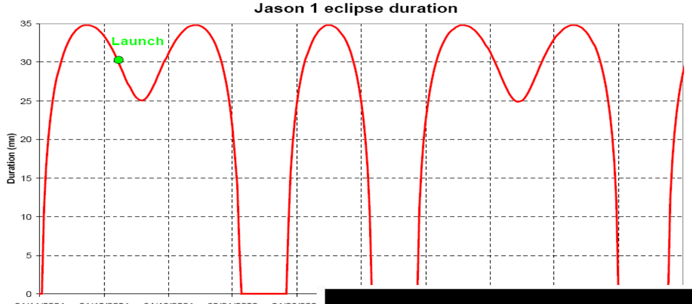
System drivers / Orbits



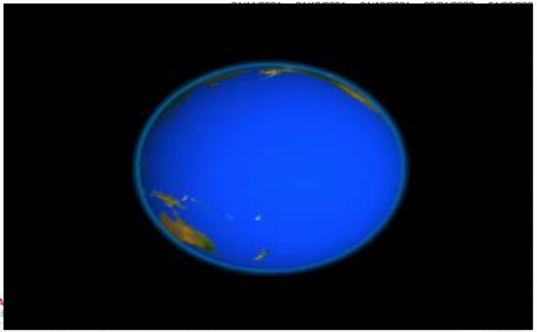
∅ Sun = 109 x ∅ Earth

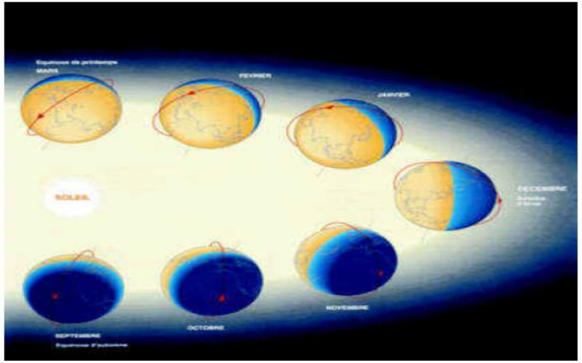
LEO (Low Earth Orbit) / Scientific applications -

- Orbit
  - Type: Circular
  - 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





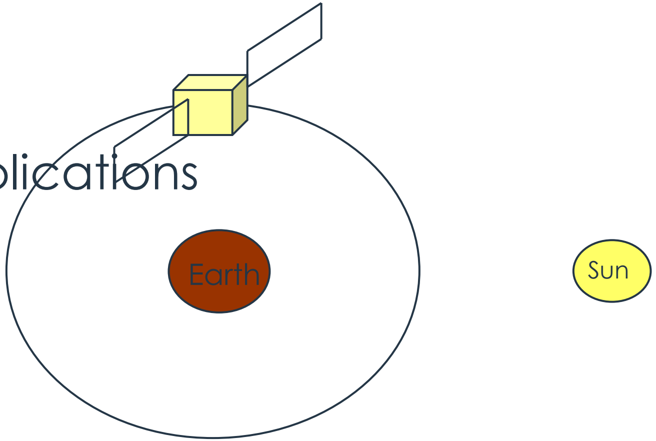
- Mission duration
  - 3 to 5 years

- Example(s): Sentinel, CryoSat, …

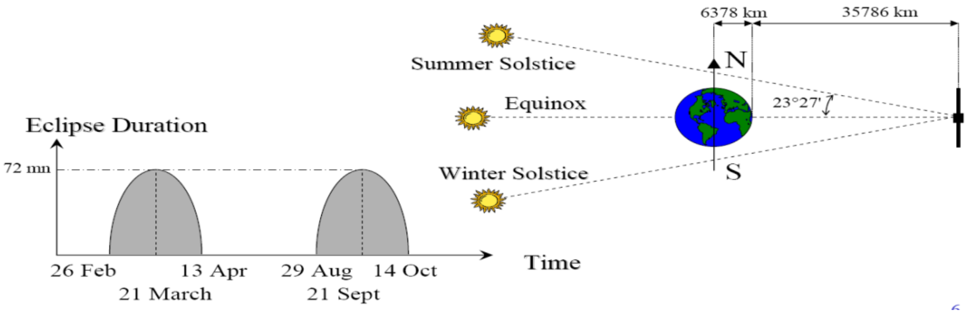
Introduction / EPS general information

System drivers / Orbits

GEO (Geostationary Orbit): Telecom applications



- Orbit
  - Type: Circular
  - Altitude: 35786 km
  - Duration: 24 hours
  - Medium sensitivity to radiations
- Eclipses
  - Less then 1% of mission duration
  - Only during equinoctial periods
  - From few to 72 min max

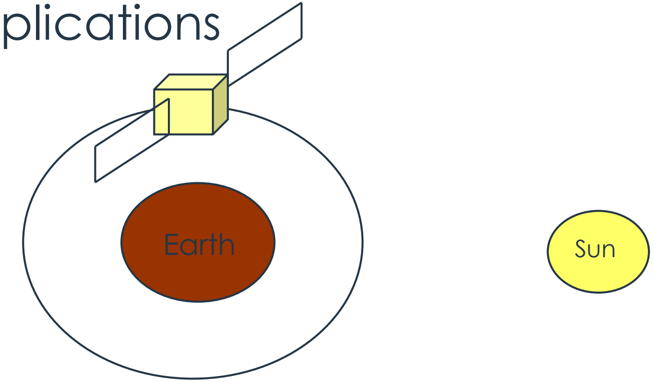


- Mission duration
  - 15 years
- Example(s): Spacebus based satellites, …

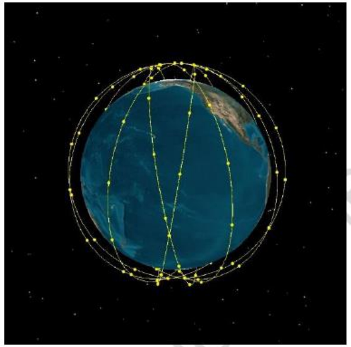
Introduction / EPS general information

System drivers / Orbits

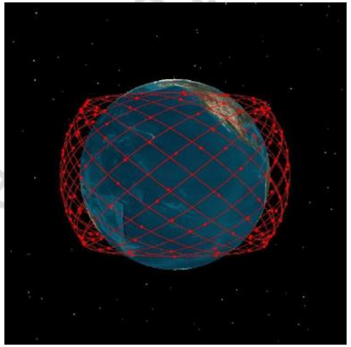
MEO (Medium Earth Orbit): GPS / TELECOM applications



- 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



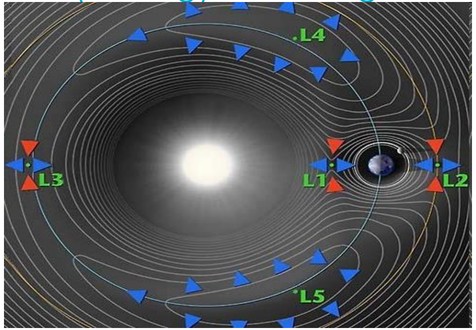
Inclined Orbit

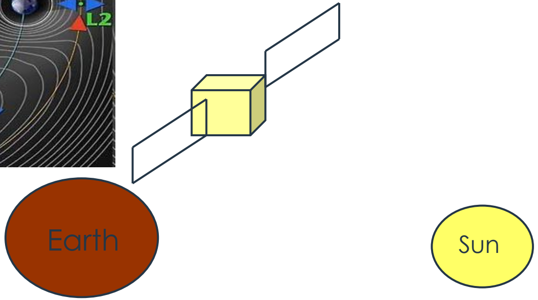
Introduction / EPS general information

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*106 km



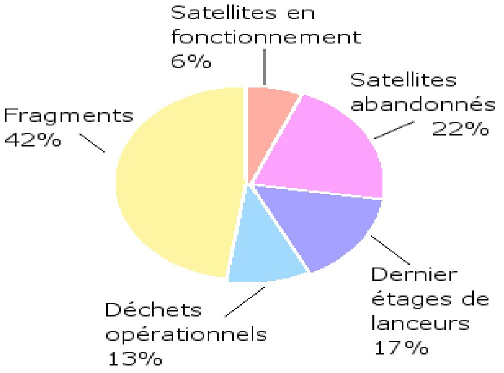


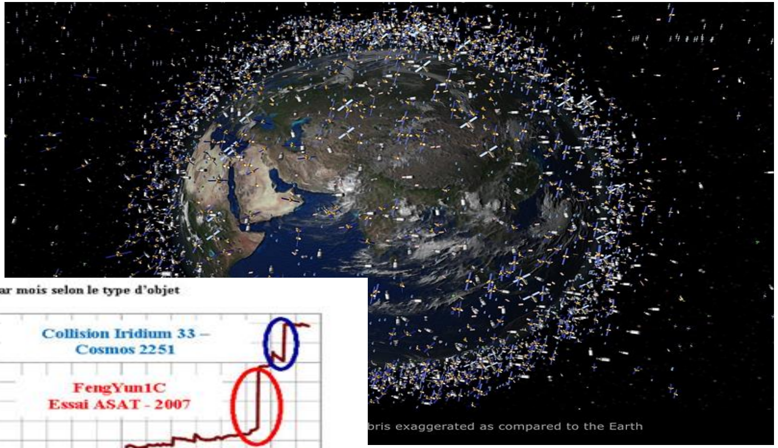
- Eclipses
  - None
- Mission duration
  - 3 years
- Example(s): Herschel (L2), Planck(L2), Gaia(L2),…

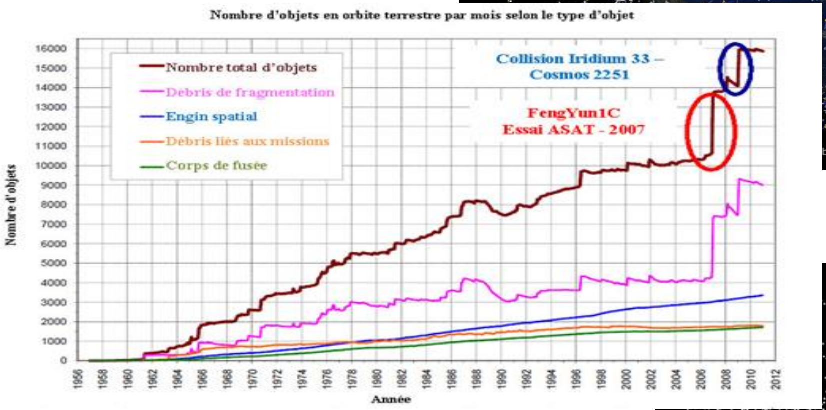
Introduction / EPS general information

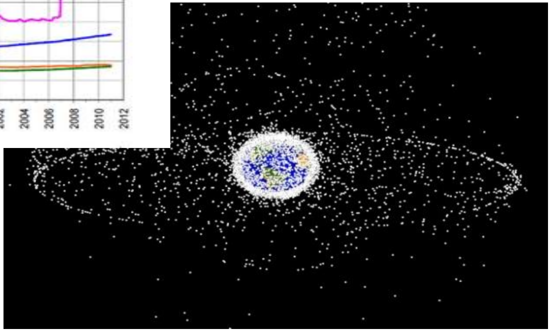
System drivers / Orbits

- μ-meteorite & debris







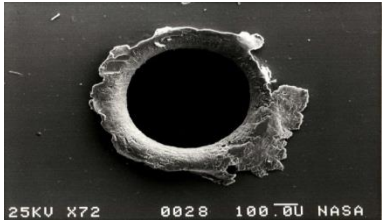


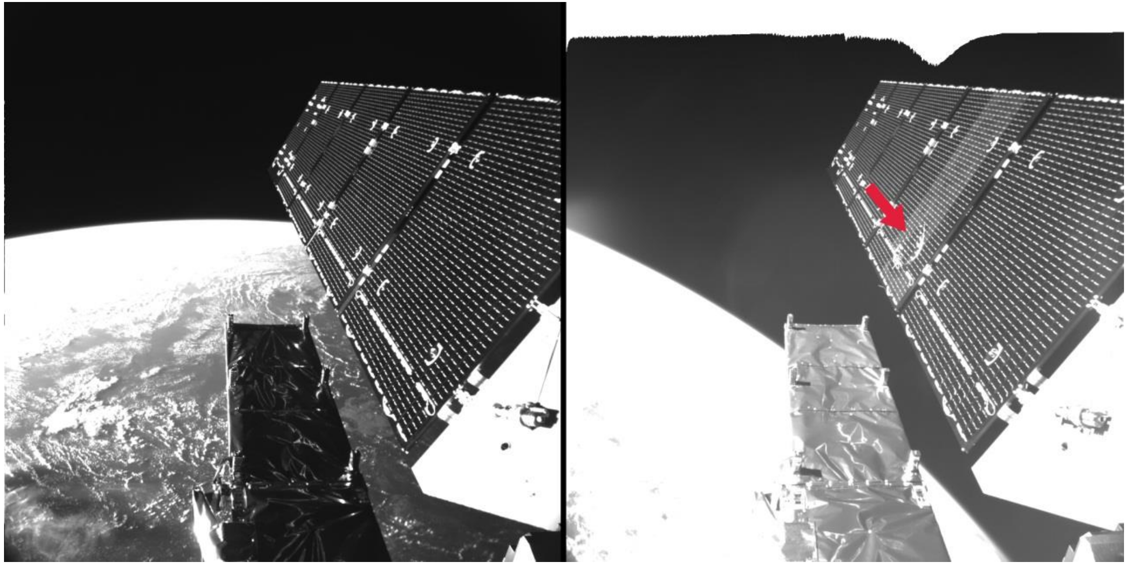
- 15 000 parts > 10cm
- 300 000 parts < 10 cm
- Large concentration between 700 & 1000 km

Introduction / EPS general information

System drivers / Orbits

- LOS (French rule) to avoid generation of new debris
  - Controlled desorbitation or
  - Parking in specific orbit with complete (propulsion and electronic) passivation (25 years in LEO, 100 years in GEO)

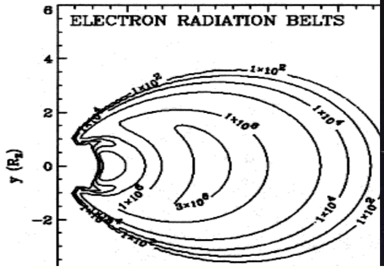


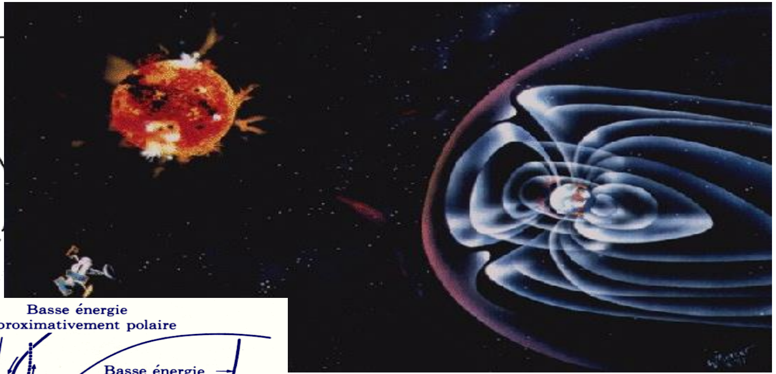


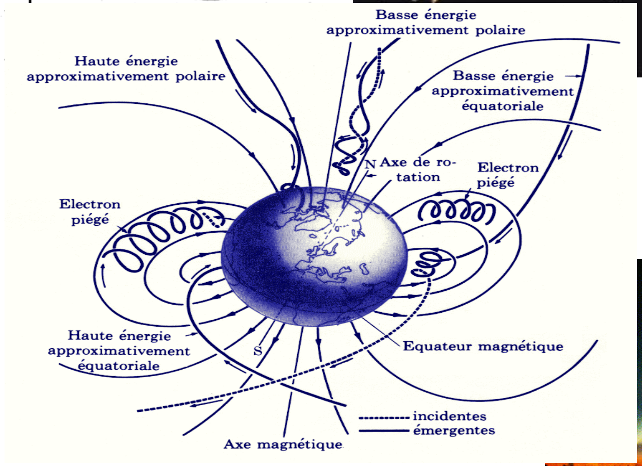
Introduction / EPS general information

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

Effects

Total dose
Decreasing of semi-conductor performances up to destruction
SA cells, Mosfets, Bi-polar transistors, …

S.E.E.
Transient effect on semi-conductors, may lead to its destruction
Mosfets, Memory, Amplifiers, …

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

Introduction / EPS general information

System drivers / Orbits

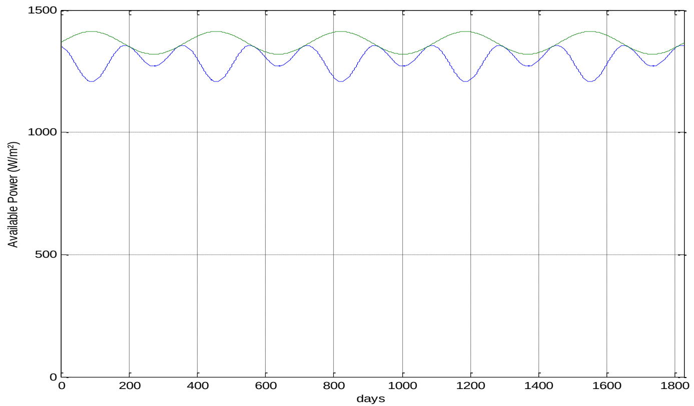
- Solar flux, which decreases with the square of the distance to the sun

	Distance (AU)	Radius (Earth)	Solar fluw (W/m²)
Sun	0	109	
Mercury	0.39	0.38	$9.3\ 10^3$
Venus	0.72	0.95	$2.6\ 10^3$
Earth	1.0	1.00	$1.36\ 10^3$
Mars	1.5	0.53	582
Jupiter	5.2	11	48.7
Saturn	9.5	9	13.5
Uranus	19.2	4	3.6
Neptune	30.1	4	1.5
Pluto	39.5	0.18	0.86

Earth radius = 6378 km

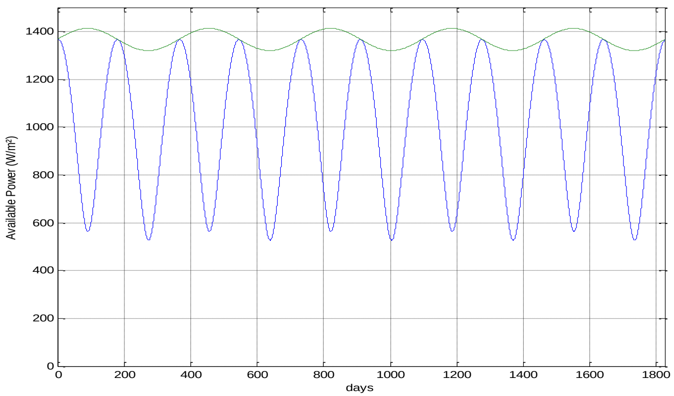
1 UA = 149 597 870 km

Introduction / EPS general information

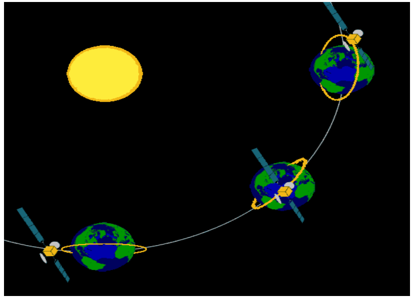


SA flux (sun-synchronous orbit)
- > Min SA flux = 1220 W

orbit



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



Introduction / EPS general information

System drivers / Missions

- (Life) duration
  - From few minutes (launchers) to 15 years (Geo)
  - 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

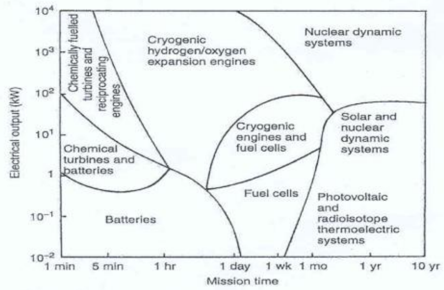


Figure 10.1 Power outputs: mission duration relationship between energy source and appropriate operational scenario [2] (From Angrist, S. W. (1982) *Direct Energy Conversion*, 4th edn, Copyright Allyn and Bacon, New York)

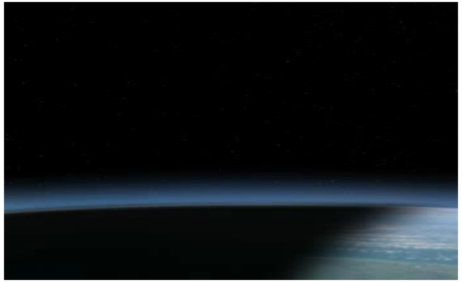
Reliability requirements

- EPS may be requested to be
  - SPF 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
Latchning 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 Subsystem	PSS
Regulaterd 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 System (incl. SADM)	43	4 %
Distribution	21	2 %
Battery NiH2	132	12 %
Solar Array	100	9 %
Power TOTAL	**296**	**27 %**

Data from CNES

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 System (incl. SADM)	10	2 %
Distribution	29	6 %
Battery NiCd	45	10 %
Solar Array	42	9 %
Power TOTAL	**126**	**27 %**

Data from CNES

Illustration CNES

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 System (incl. SADM)	6.5	6 %
Battery LiIon	4	4 %
Solar Array	6.5	6 %
Power TOTAL	**17**	**16 %**

Data from CNES

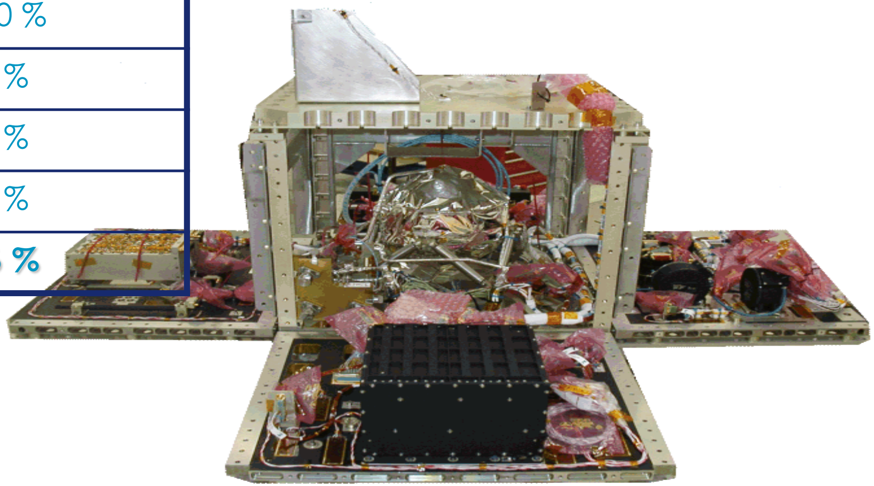


Illustration CNES

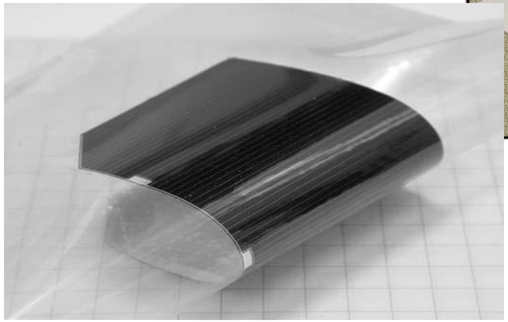
Agenda

1. Introduction
   - Presentation of Thales Alenia Space Belgium (ETCA)
   - Presentation of myself
   - EPS – general information
2. **Primary power sources**
   - Solar cells & solar arrays
   - Fuel cells
   - RTG
   - Others
3. Secondary power sources - batteries
4. Power Management, Control & Distribution
   - Architecture
   - PCU / PCDU
5. Power budget – practical exercise
6. Conclusions

Primary power sources / Solar cells & arrays

SA cells

- A solar cell is composed of a semi-conductor material and converts photons to electrons
- Photovoltaic 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 excess 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



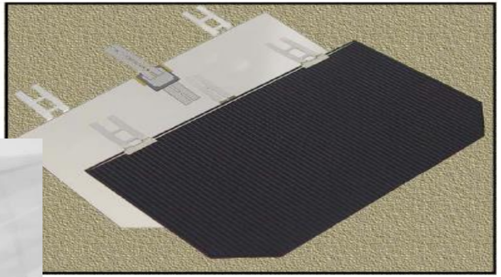
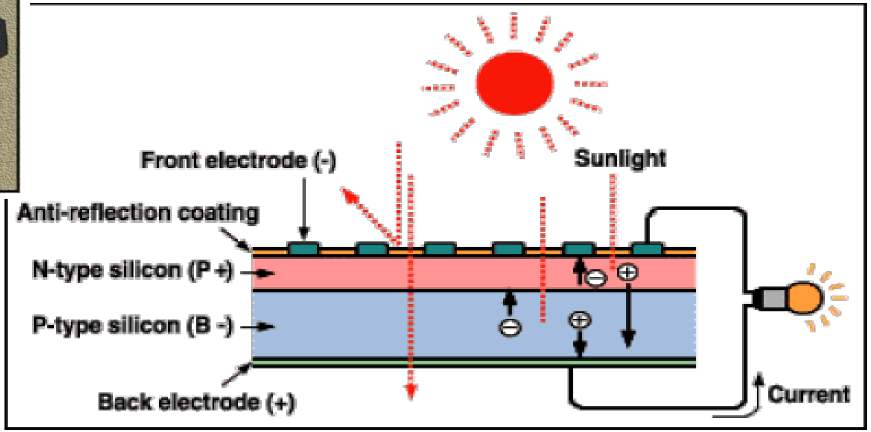


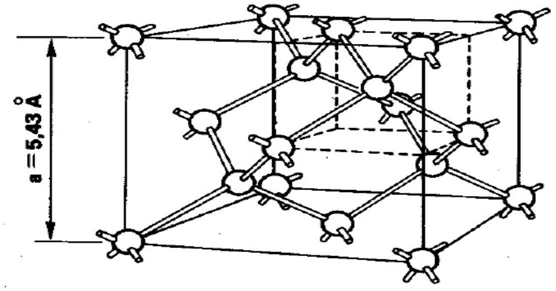
Illustration SPECTROLAB



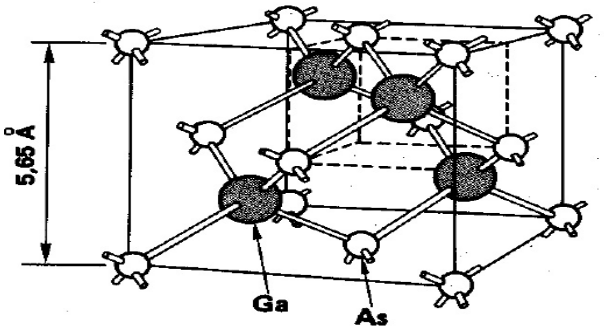
Primary power sources / Solar cells & arrays

Semi-conductors properties (1)

- Most common semi-conductors: silicium and arsenide-gallium (AsGa)
  - Cubic crystalline structures

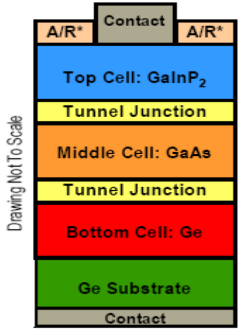


Silicium



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

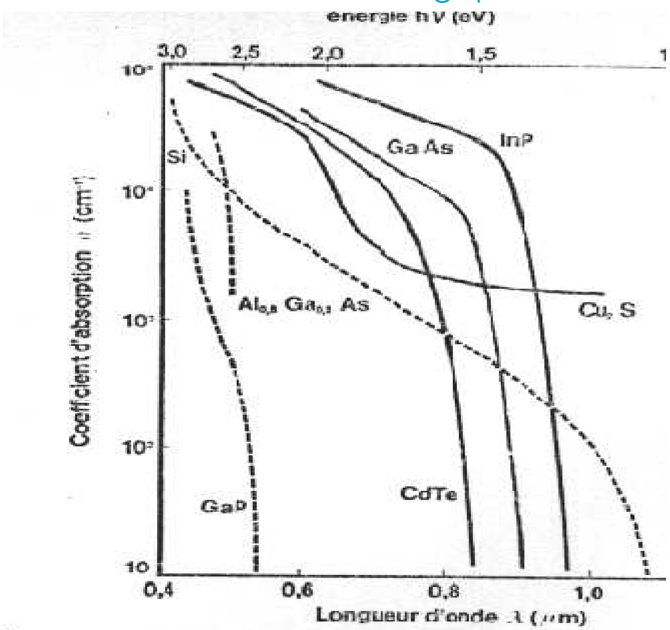


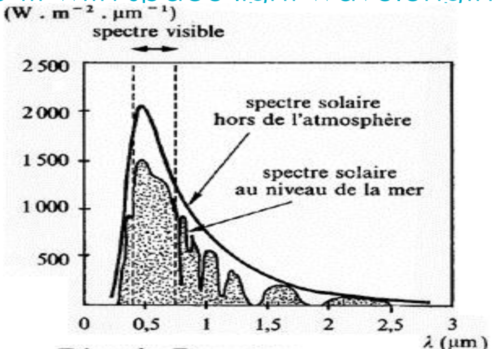
*A/R: Anti-Reflective Coating

Primary power sources / Solar cells & arrays

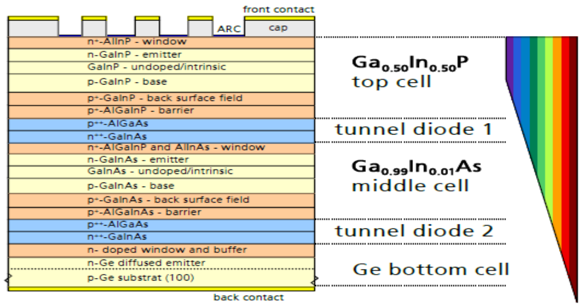
Solar flux

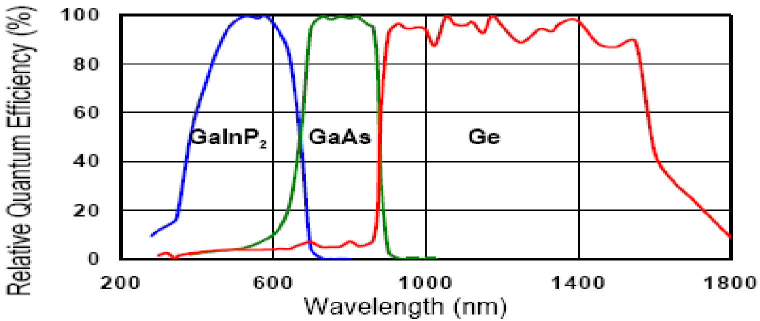
- Semi-conductor gap is chosen to fit with space light wavelength





D'après Bouyssy

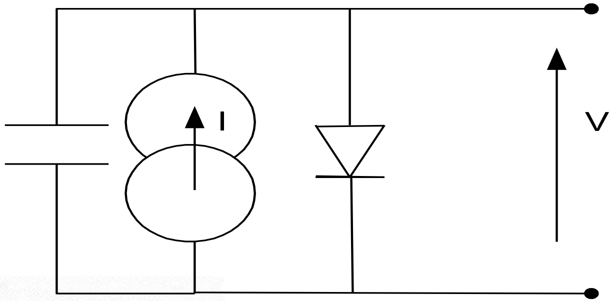




Primary power sources / Solar cells & arrays

Equivalent circuit diagram

- Each solar cell is equivalent to
  - a current source in parallel with
  - a capacitor (variable) and
  - a diode



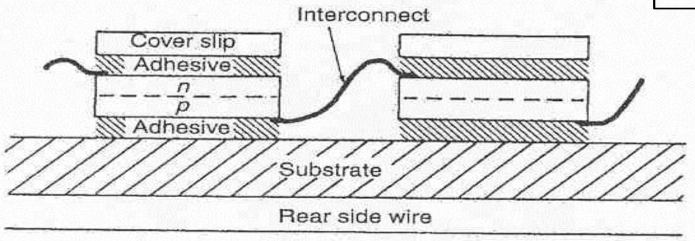
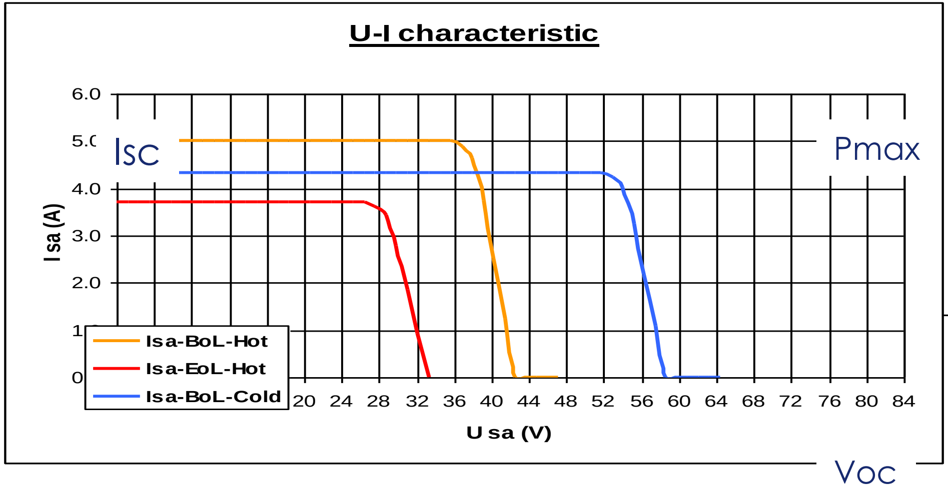
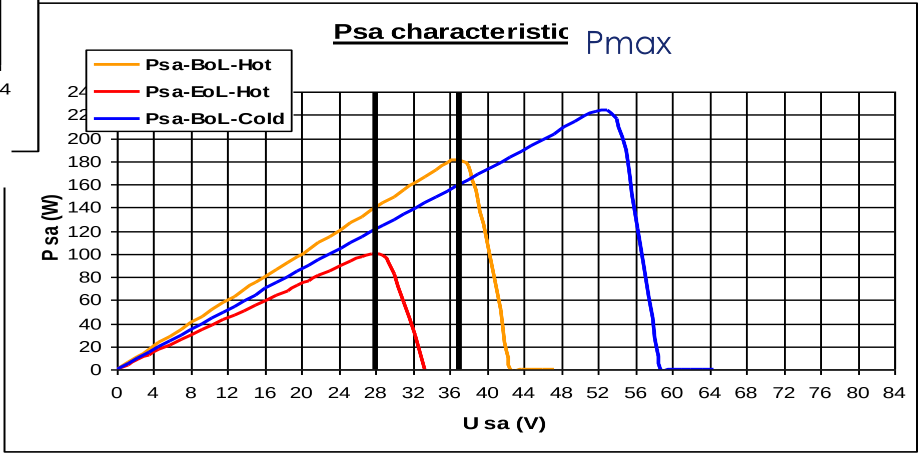


Figure 10.3 Schematic of a typical solar cell assembly

Primary power sources / Solar cells & arrays





Pmax is largely depending of temperature & ageing

Primary power sources / Solar cells & arrays

Efficiency

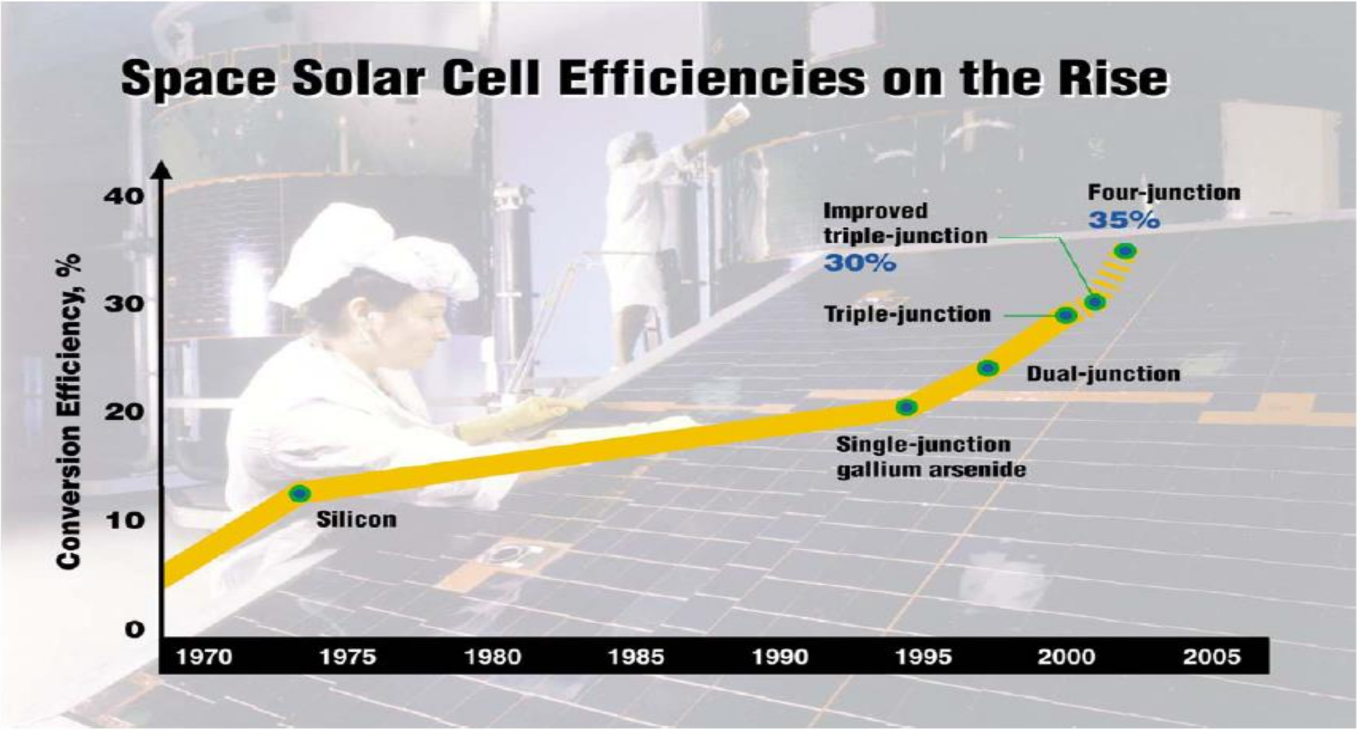


Illustration SPECTROLAB

Primary power sources / Solar cells & arrays

Efficiency degradation factors

- Mission lifetime
  - Loss of power: 1% to 2% every year (depends of the orbit)
- Radiation effects

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

Parameters	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$
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

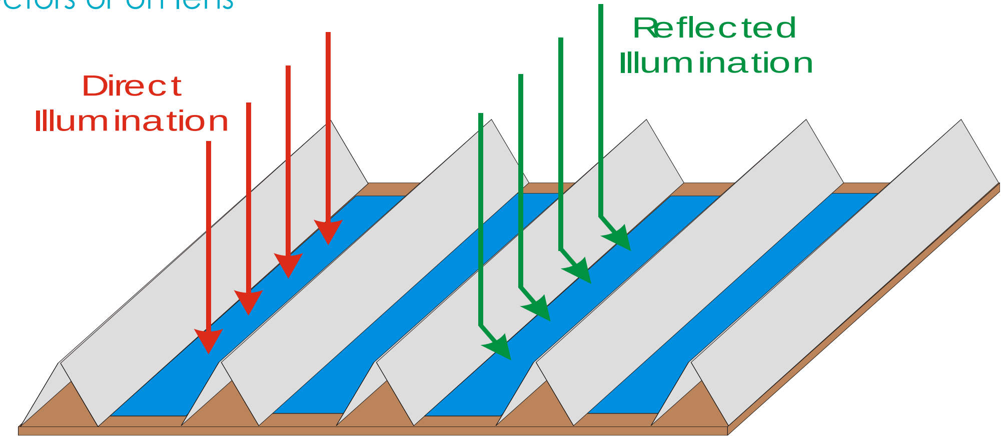
Illustration SPECTROLAB

- 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)

Primary power sources / Solar cells & arrays

Concentrators / Advantages

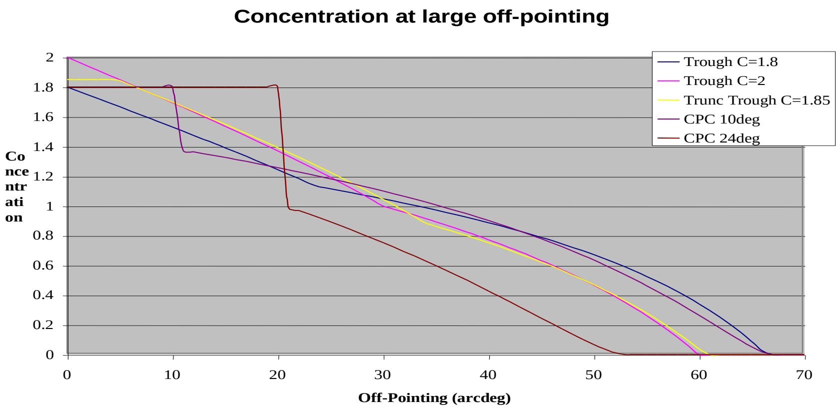
- Concentrate SA flux on SA cells
- Reduce SA cells surface
- Based on reflectors or on lens

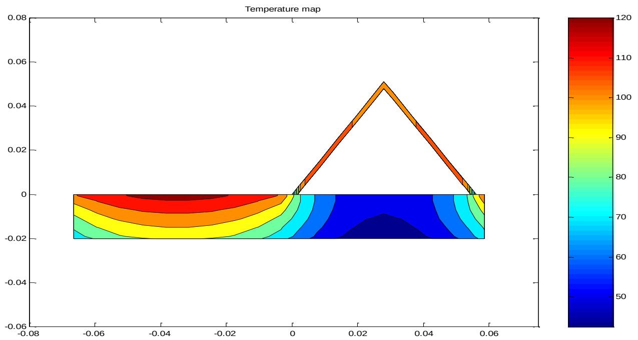


Primary power sources / Solar cells & arrays

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 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 (1)

- 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

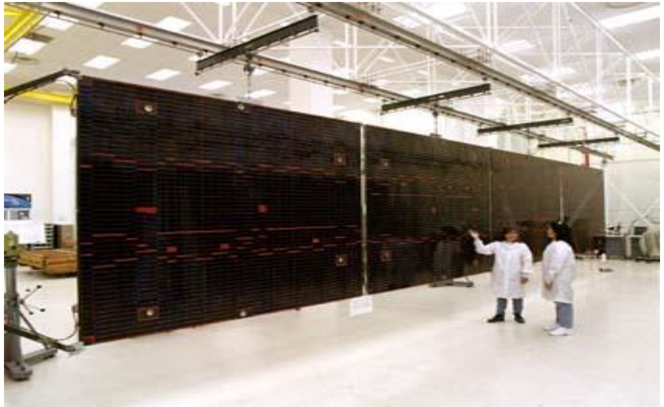
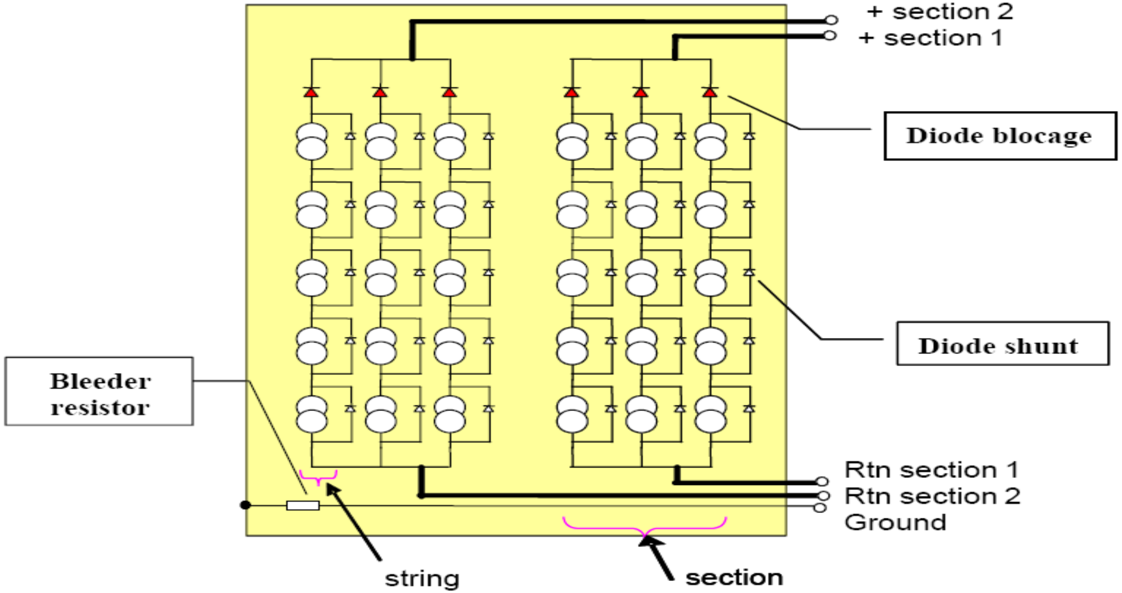
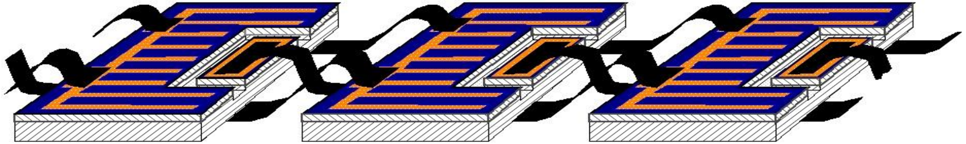


Illustration Thales Alenia Space

Primary power sources / Solar cells & arrays





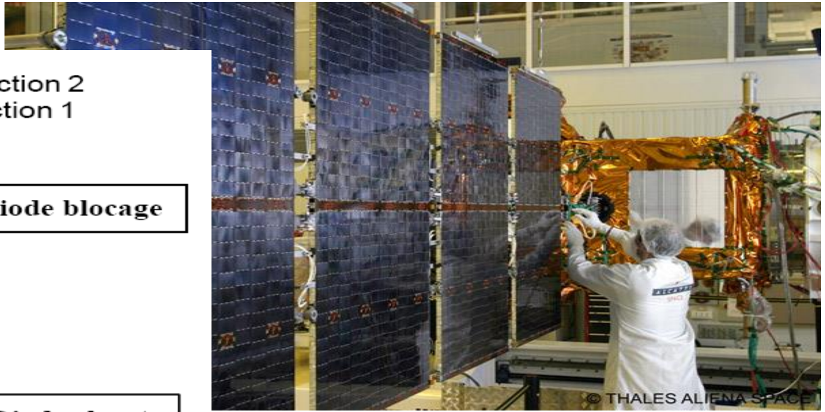
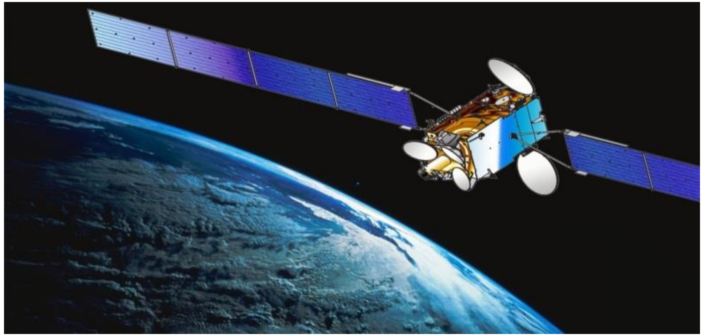


Illustration Thales Alenia Space

Protection against shadowing

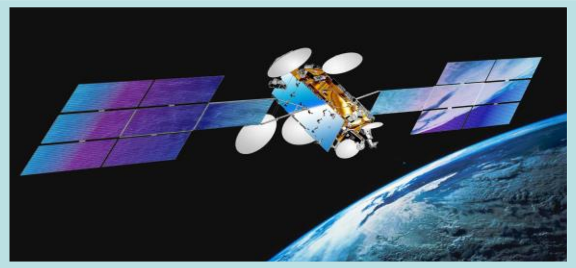
Illustration SPECTROLAB

Primary power sources / Solar cells & arrays

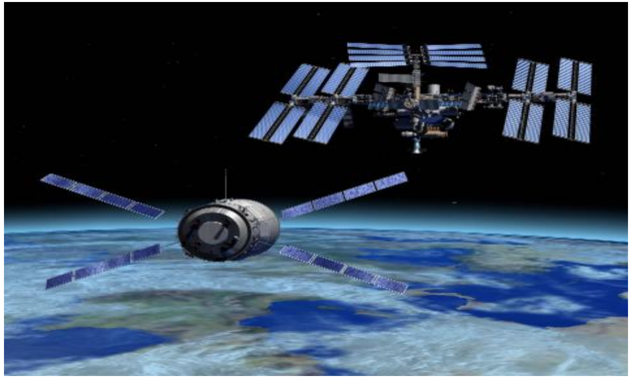


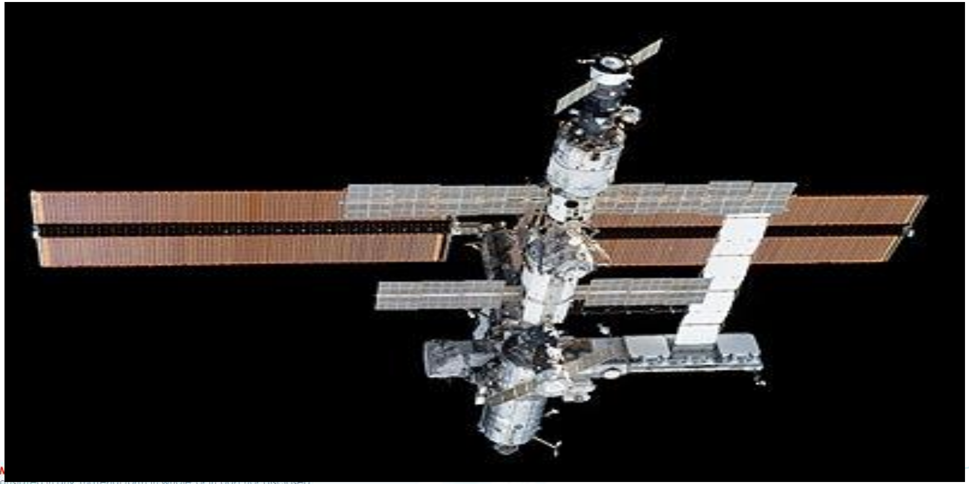
Solar arrays (3) – Types

- 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 orbit)
  - 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

Solar Arrays (4) – mechanisms (hold-down & release)

- SA are fold during launch
- Deployment is
  - Initiated by pyro actuation (or thermal knifes)
  - Controlled by the use of hinge mechanisms

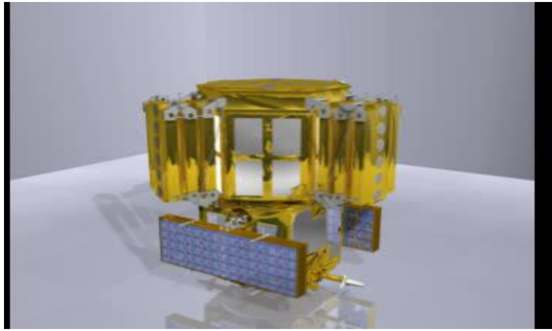


Illustration Thales Alenia Space

Solar Arrays (4) – mechanisms (orientation)

- Mobile SA is controlled by SADM
- Current is transferred to S/C main part via BAPTA
- Tensioning wires – achieve minimum fundamental frequency of the array (AOCS constraints)

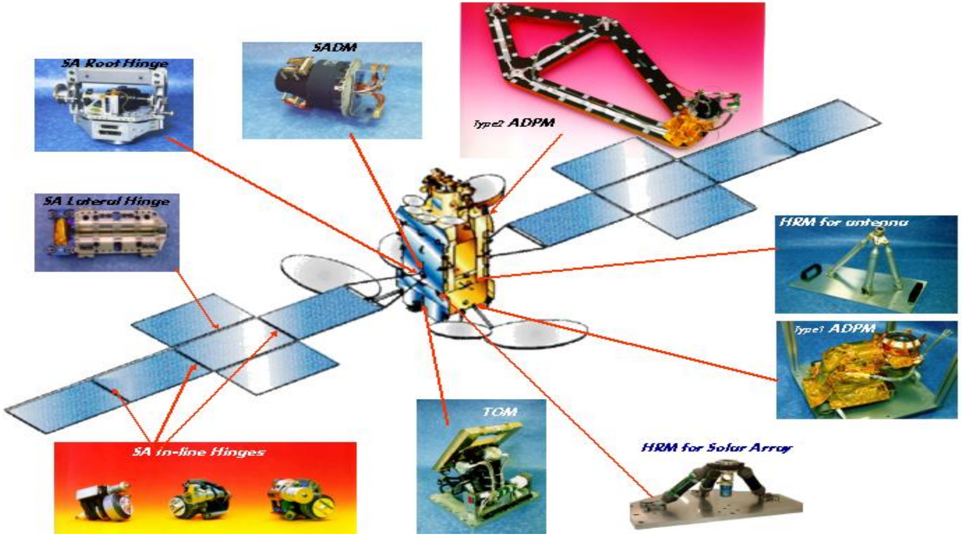


Illustration Thales Alenia Space

Primary power sources / Solar cells & arrays

Solar arrays (5) – thermal interfaces

- SA cell temperature directly impacts its efficiency
- Temperature is linked to
  - The incoming flux
    - Direct solar flux
    - Albedo
    - 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
  - Sizing of Solar Arrays requires simulation tools
    - e.g. the delivered power is function of the temperature, which is itself function of the power
- Temperature cycling (~100 °C in few minutes) induces thermal stress (differential expansion between substrate and cell, which are made of different material) on interconnections (major array failure hazard)

Primary power sources / Solar cells & arrays

Solar arrays (6) – 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 (oxidation) 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, …

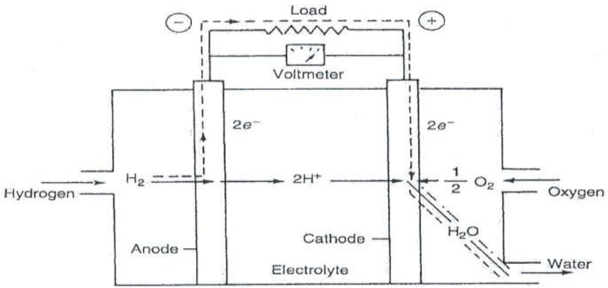


Figure 10.10 Schematic of a hydrogen/oxygen fuel cell. At the anode–electrolyte interface, hydrogen dissociates into hydrogen ions and electrons. The hydrogen ions migrate through the electrolyte to the cathode interface where they combine with the electrons that have traversed the load [2] (From Angrist, 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

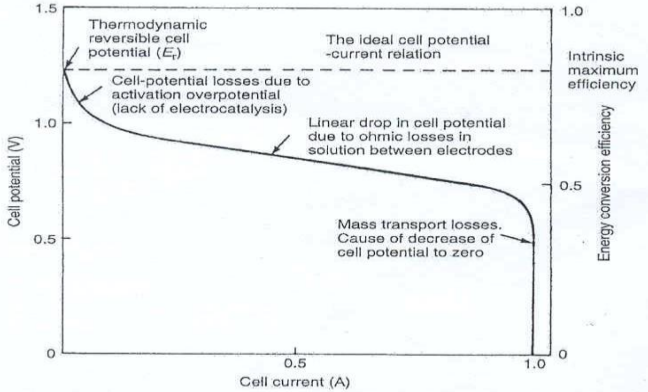


Figure 10.11 Typical cell potential and efficiency–current relation of an electrochemical electricity producer showing regions of major influence of various types of overpotential losses (Source [10])

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 is important (very low orbits) -> reduction of propellant used for orbit control

Primary power sources / RTG

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

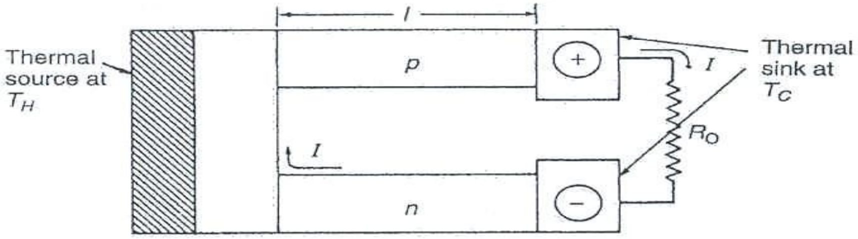


Figure 10.12 Schematic diagram of a semiconductor radioisotope generator (From Angrist, S. W. (1982) *Direct energy conversion*, 4th edn, Copyright Allyn and Bacon, New York)

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)

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

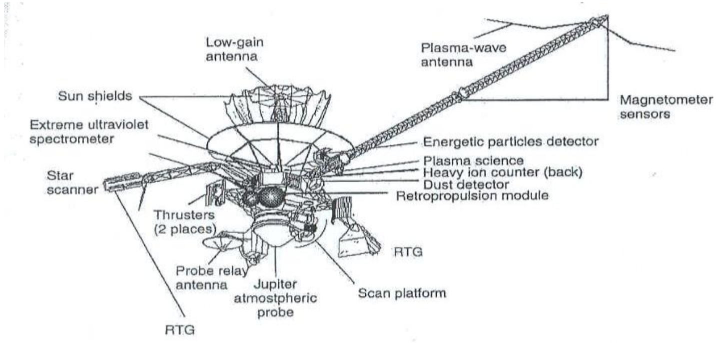
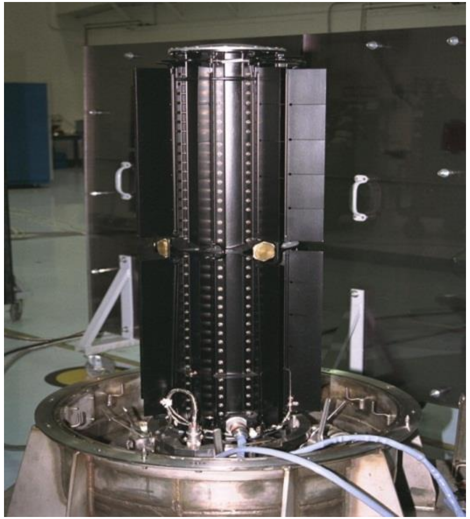


Figure 10.13 The Galileo spacecraft configuration, showing the position of the RTG sources (Courtesy of NASA/JPL/Caltech)

Primary power sources / RTG & others

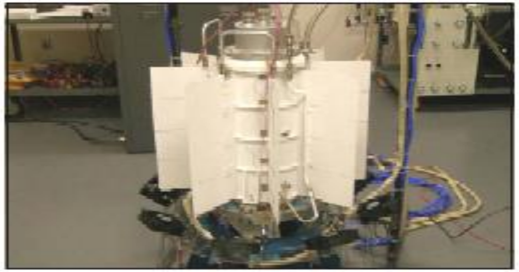
Example of RTG

Cassini (Saturn mission)	628 W	195 W/kg
Galileo probe/Ulysses	285 W	195 W/kg
Nimbus/Viking/Pionner	35 W	457 W/kg
Appolo 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

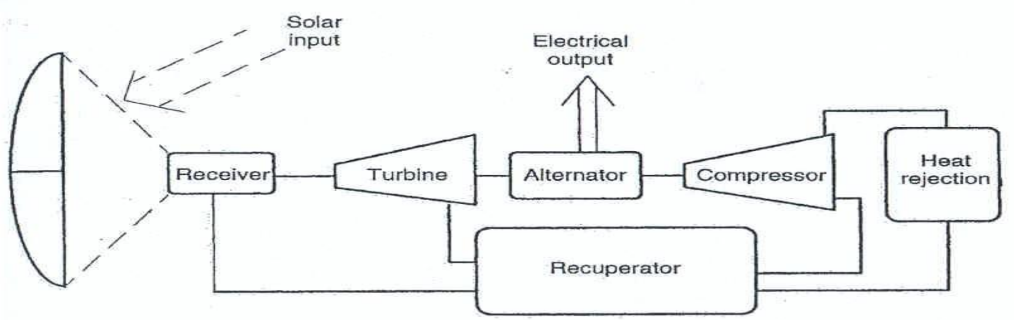


Figure 10.14 Solar dynamic Brayton cycle

Agenda

1. Introduction
   - Presentation of Thales Alenia Space Belgium (ETCA)
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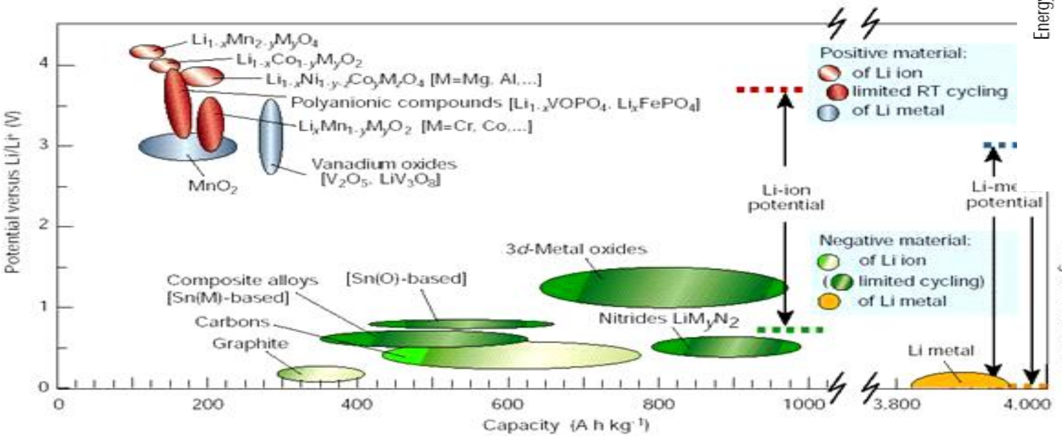
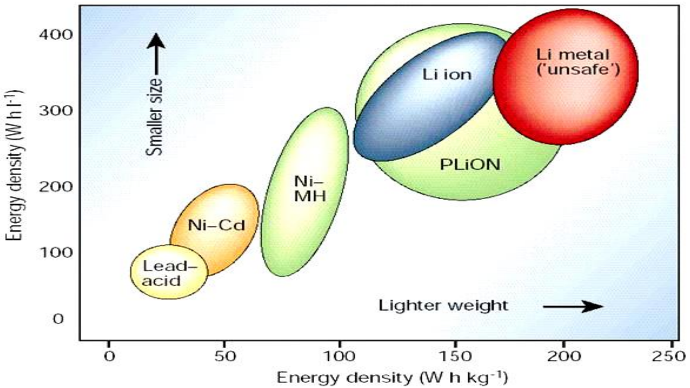
   - Fuel cells
   - RTG
   - Others
3. **Secondary power sources - batteries**
4. Power Management, Control & Distribution
   - Architecture
   - PCU / PCDU
5. Power budget – practical exercise
6. Conclusions

Secondary power sources

Accumulators

- Electromechanical devices performing a controlled chemical reaction to derive electrical energy
- Critical parameters
  - Charge/discharge rate
  - Depth of Discharge
  - Extent of over-discharging
  - Thermal sensitivity to each of these parameters

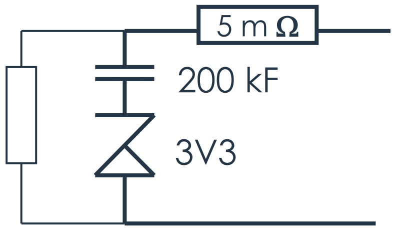


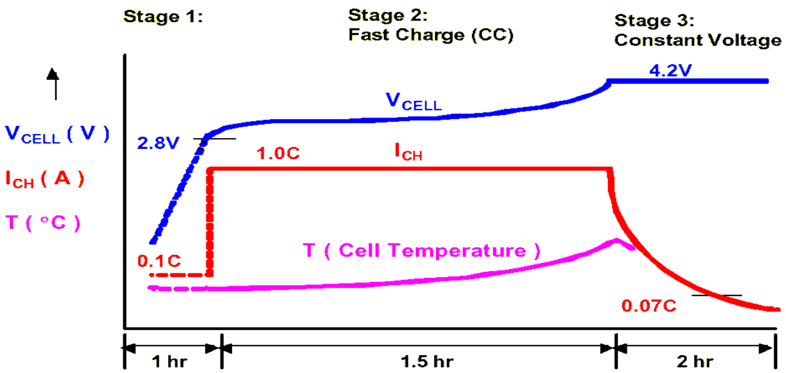


Secondary power sources

Accumulators

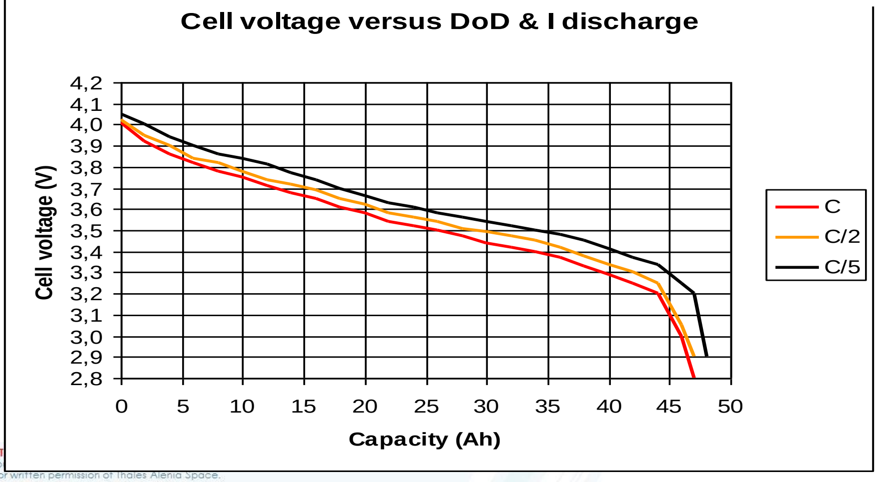
- Elementary Battery model





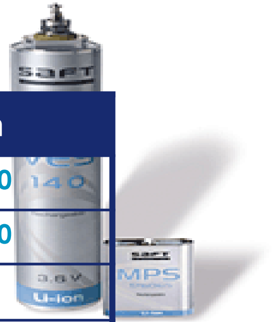
Typical Characteristics

- Capacity
  - 1.5Ah -> 100Ah
- Voltage range
  - 4.1V -> 3.3V
- Series Resistance
  - 1mΩ -> 10m Ω
- Leakage current
  - 0mA -> 5mA



Secondary power sources

Comparison of performances

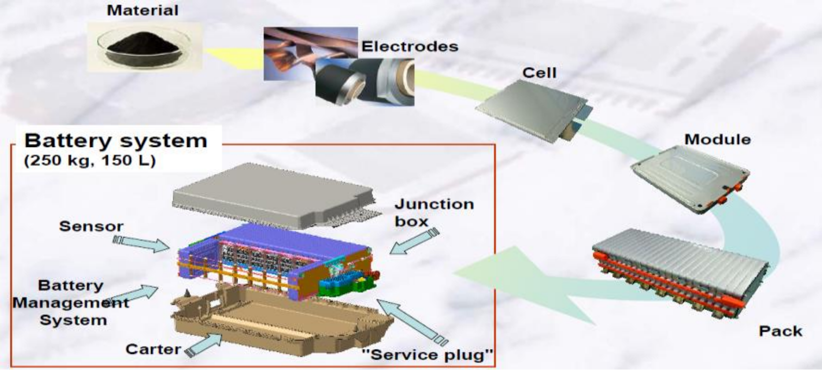


Type	NiCd	NiH2	Li-Ion
Energy/kg (Wh/kg)	30-40	55-65	100-130
Energy/l (Wh/l)	110	80	200-250
Discharge voltage mean (V)	1.25	1.25	3.5
Working temperature (°C)	[-5;+15]	[0;+10]	[+15;+25]
Charge current (A)	⇒ C/10 (GEO) ⇒ C/2 (LEO)	⇒ C/8 (GEO) ⇒ 0.7C (LEO)	C/10 ⇒ C/3
Discharge current (A)	⇒ 2C	⇒ C	⇒ C
Energy efficiency	75	75	90
Max. voltage (A)	1.55	1.6	4.0
Min. voltage (A)	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
    - 22-37 V in LEO
    - EUROSTAR 2000: 42.5 V
    - EUROSTAR 3000 & SPACEBUS 3000: 50 V
    - SPACEBUS 4000: 100 V
  - In parallel to reach the desired capacity



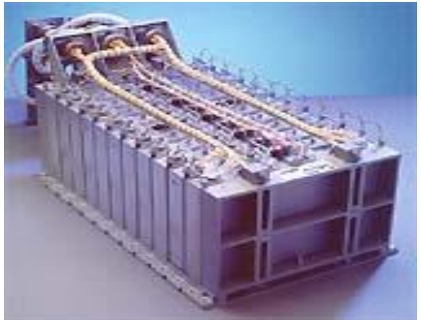
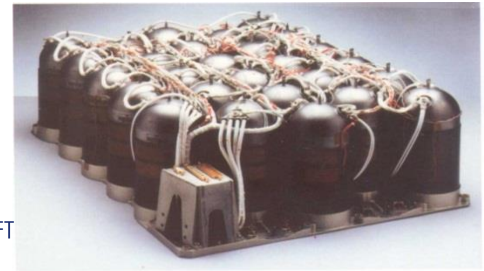


Illustration SAFT



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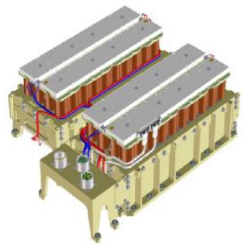
NICKEL HYDROGEN BATTERY

Illustration SAFT

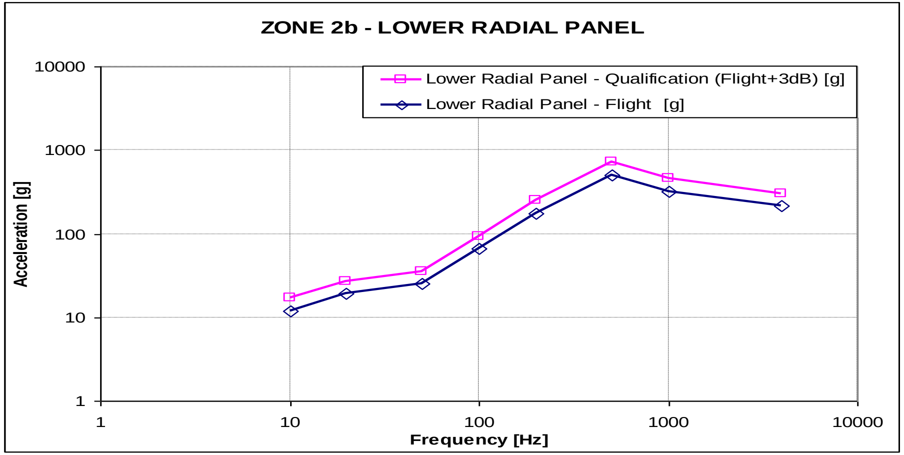
Secondary power sources

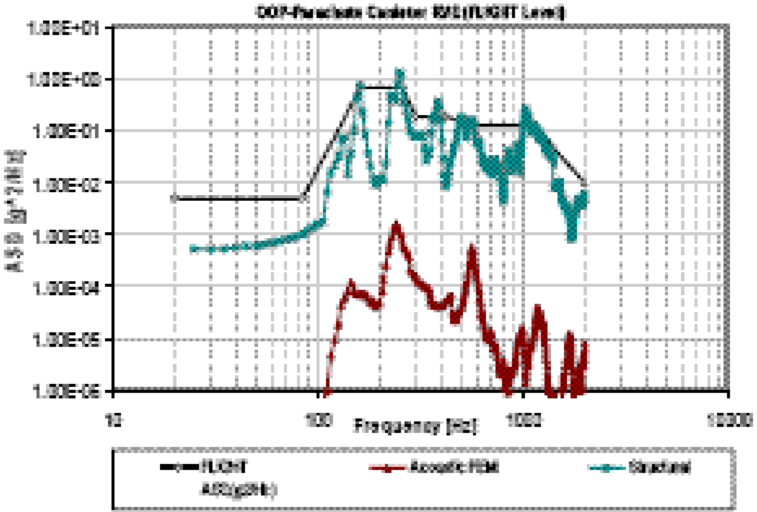
Stand alone battery



Battery accommodation

- Mechanical & thermal drivers
  - The structure shall be rigid (launch environment)
  - The structure shall allow the homogeneity of the temperature





16/11/2017
Ref. = Ref.: VLR/080066_0900
Ref. Model = 83230347-DOC-TAS-EN-005

Secondary power sources

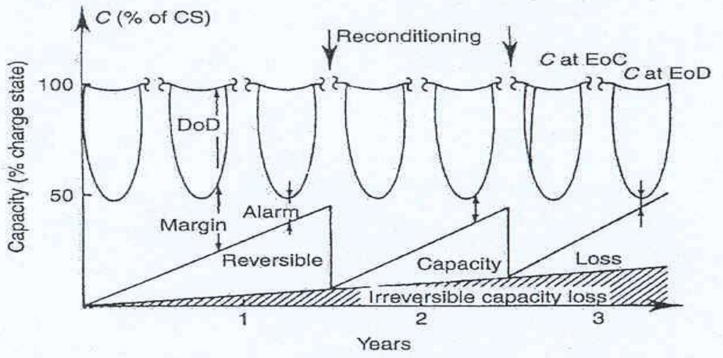
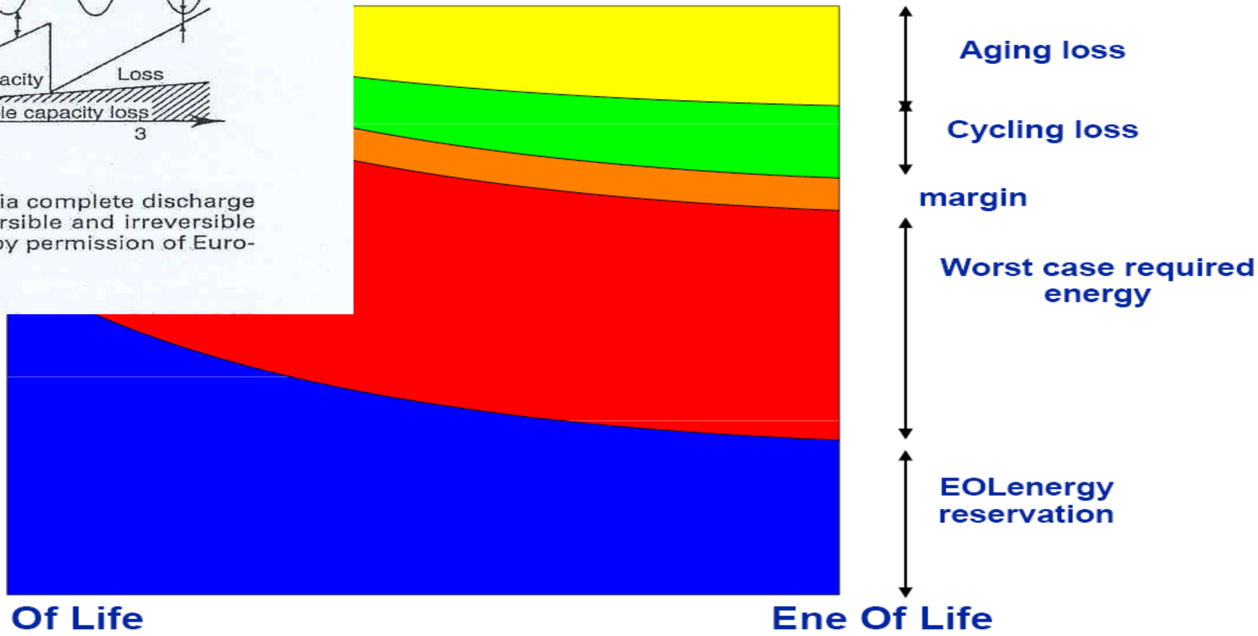


Figure 10.16 Battery reconditioning via complete discharge to improve battery capacity. Both reversible and irreversible capacity loss occurs [17] (Reproduced by permission of European Space Agency and P. Montalenti)



Secondary power sources

BoL	SAFT NiCd VOS 40	SAFT NiH2 93 AN	SAFT LiIon VOS140	SAFT LiIon MP76065	SONY LiIOn 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 %

Data CNES

Secondary power sources

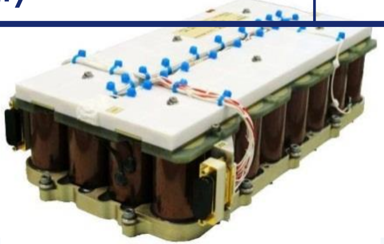
BoL	SPOT5	EURASIASAT	STENTOR	SKYBRIDGE
Configuration	24s-1p VOS40	27s-1p 93AN	11s-2p VOS140	12s-4p VOS140
Capacity	46 Ah	93 Ah	80 Ah	154 Ah
Mean voltage	29 V	37 V	39.6 V	43 V
Energy	1325 Wh	3415 Wh	3168 Wh	6620 Wh
Mass	47.4 kg	66 kg	34 kg	72 kg
Dimensions	467X261X260mm	863X441X310mm	490X380X290mm	910X520X300mm
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

Data CNES

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

Illustration SAFT

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   - PCU / PCDU
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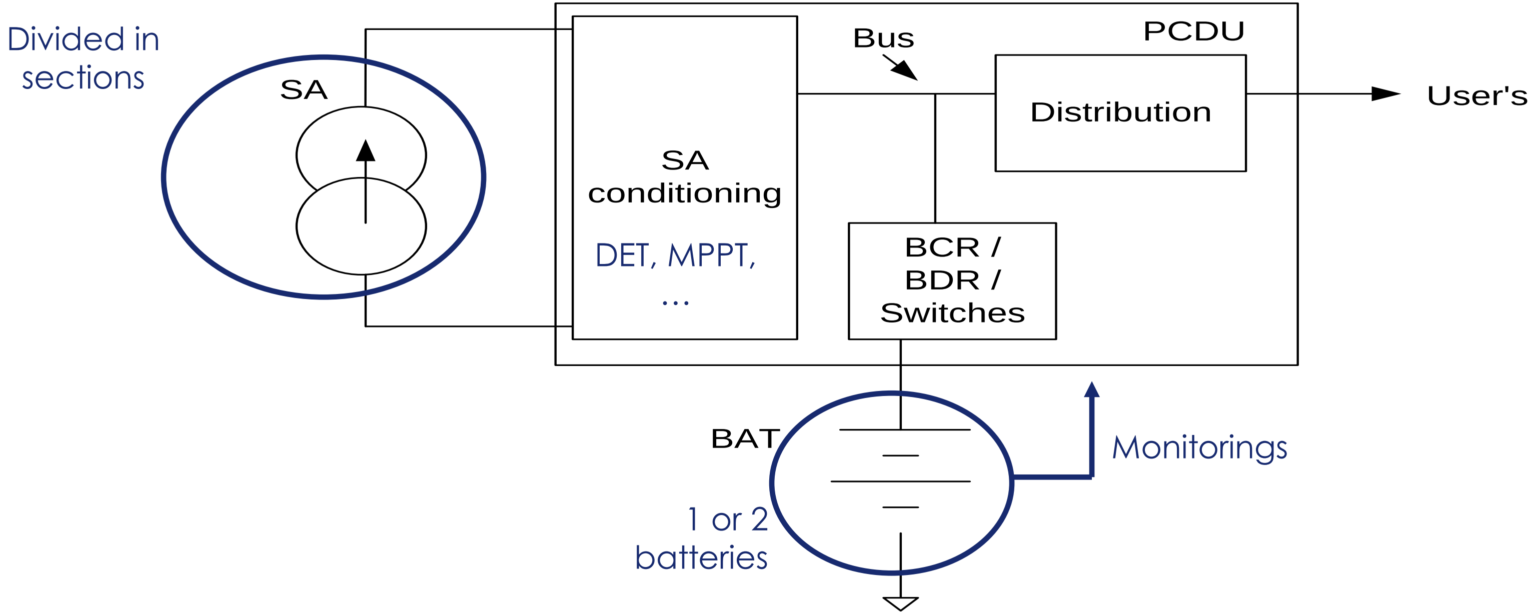
Power management, control & distribution / Architecture

Block diagram



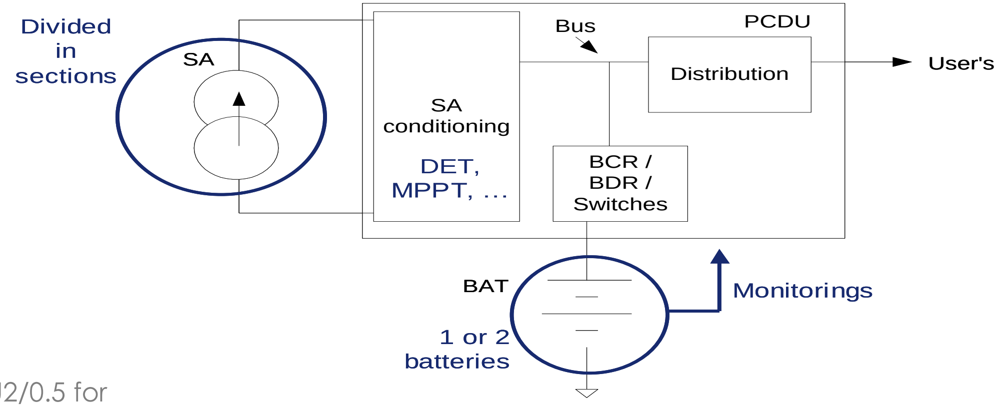
-> Operation with primary & secondary power sources whose characteristics are changing with time and conditions of operations

Power management, control & distribution / Architecture

Bus voltage selection

- Many standards
  - 28V, 50 V, 65 V, 100 V, …
  - 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 architecture may even requires two buses !!



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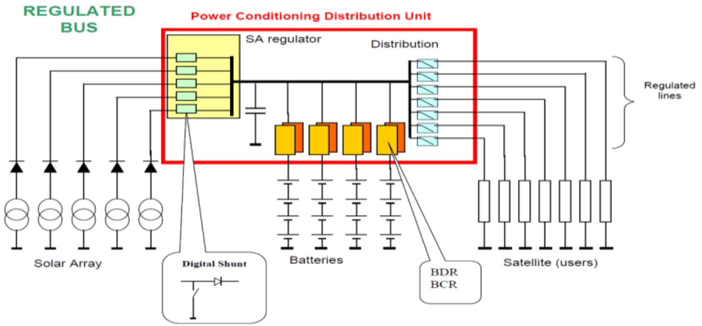
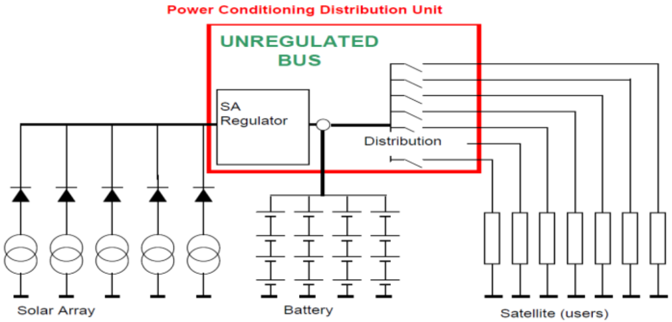
Ref. Model = 83230347-DOC-TAS-EN-005

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 einside the PCDU during clip
- 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 the
    - Thermal stability of some specific loads may requires regu (thermal management is easier in that architecture)
  - User's flight heritage

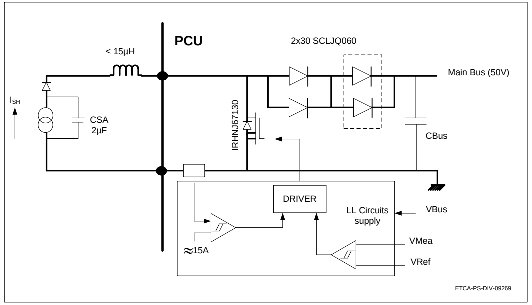




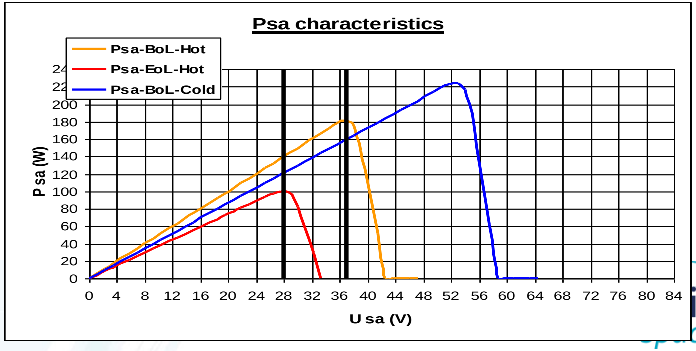
Power management, control & distribution / Architecture

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

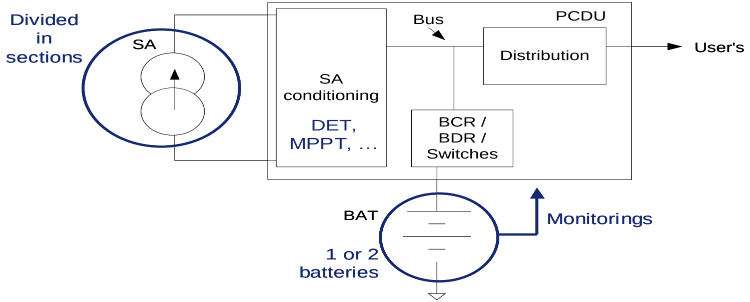


- Direct Energy Transfer (DET)
  - DET operates at the bus voltage and extracts the available power from the solar array for this precise voltage
    - Simplest solution
- PWM control of SA
  - DC/DC converter implemented between SA and bus
- Maximum Power Point Tracking (MPPT)
  - MPPT can operate in 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

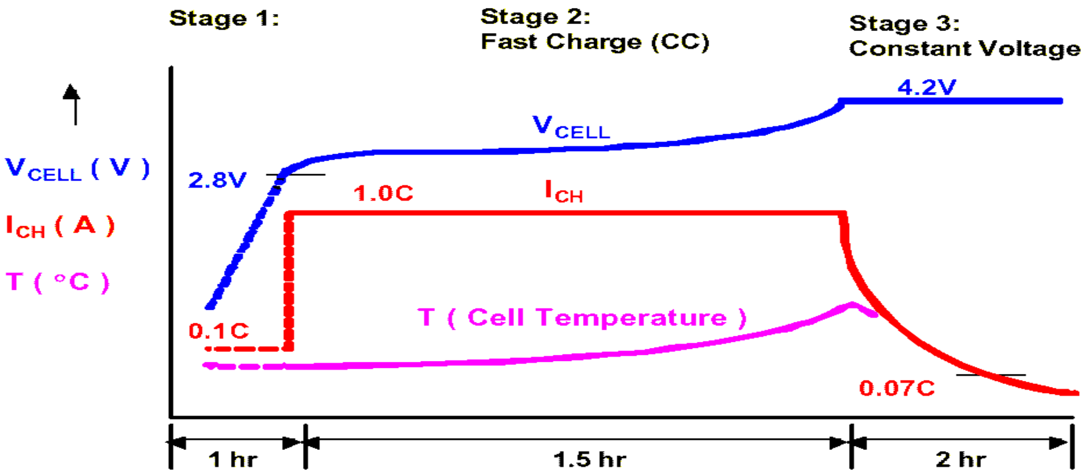


- Architecture
  - Centralized
    - Performed by OBC
    - PCDU functions limited to monitoring
  - De-centralized at PCDU level
    - Autonomous
      - PCDU ensures battery charge & protections in a reliable way
      - Voltage tapering
      - Protection against over-charge, over-discharge, over-temperature, …
    - 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
    - …

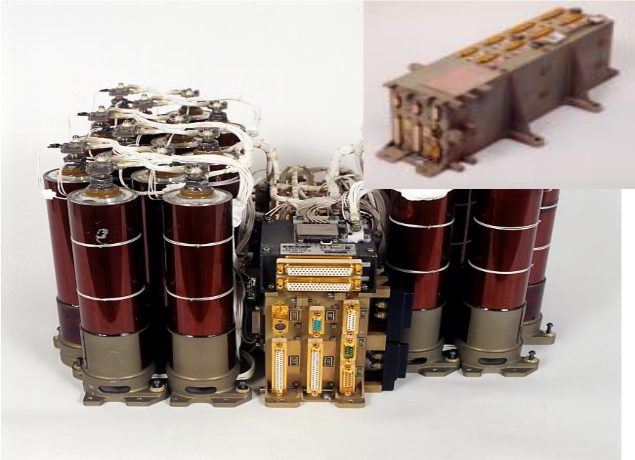
Power management, control & distribution / Architecture

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

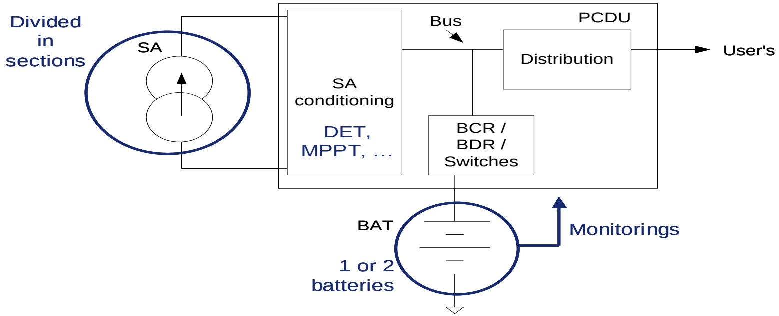
Power management, control & distribution / Architecture

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

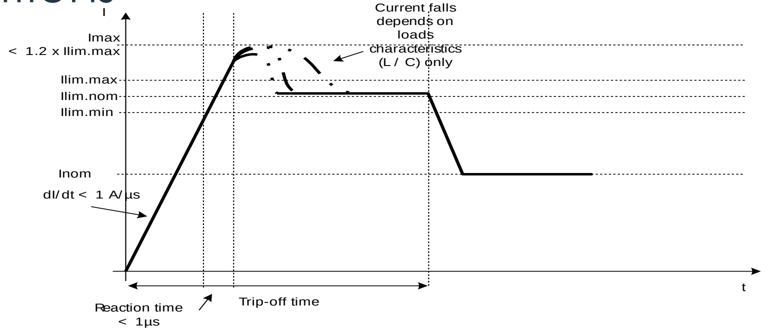
- Active switches
  - Flexible solution
  - ON/OFF switching capability
  - Control of fault current

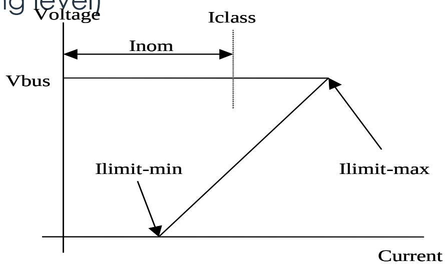


Power management, control & distribution / Architecture

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
- …





Power management, control & distribution / Architecture

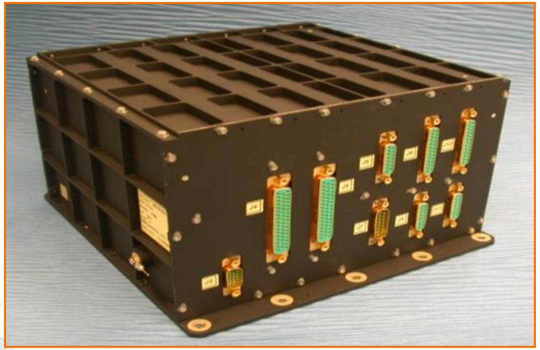
Other constituents of PCDU

- 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 protection
  - Adaptability of the distribution by paralleling of LCL's
- CNES/Astrium/TAS-F Myriade platform baseline



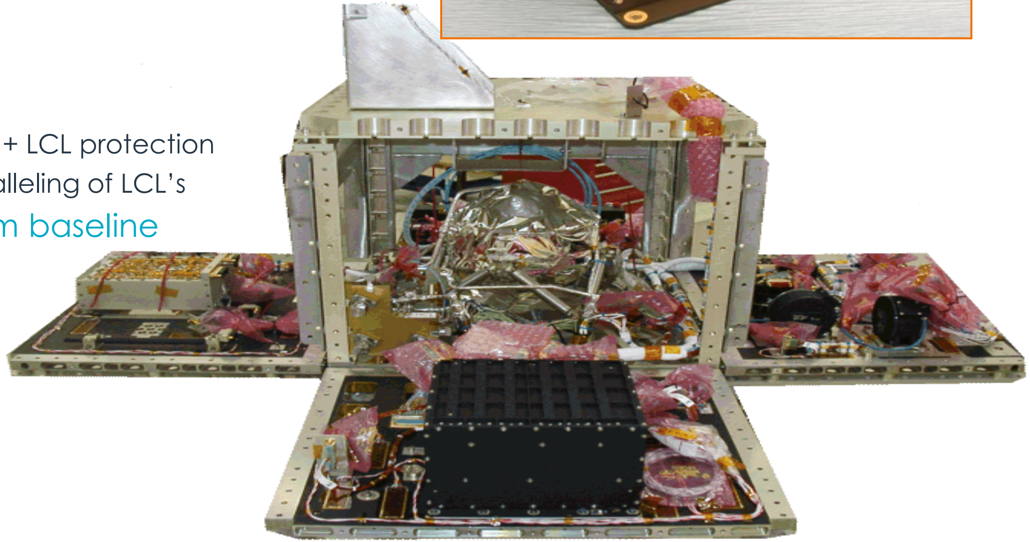
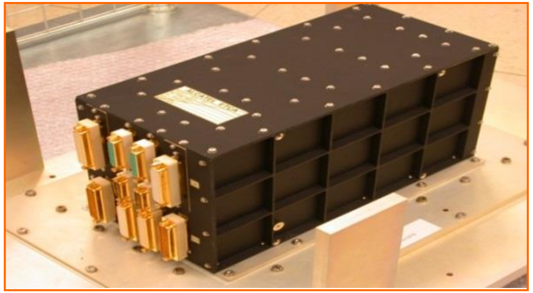


Illustration CNES

Power management, control & distribution / PC(D)U

Examples Scientific, earth observation & constellations

Adobe Acrobat Document



- 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 automative 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

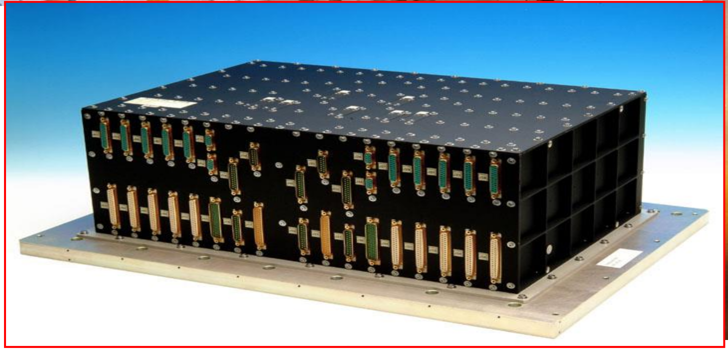


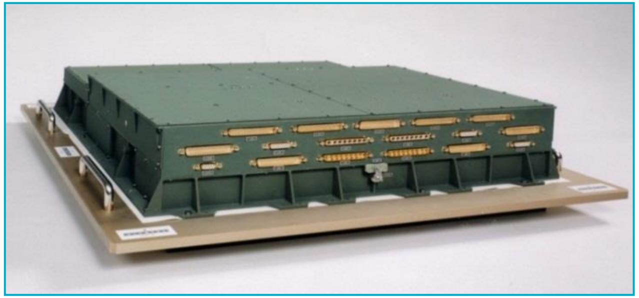
Illustration ESA

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

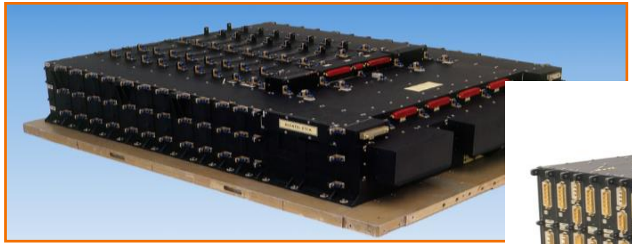


Power management, control & distribution / PC(D)U

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



Agenda

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

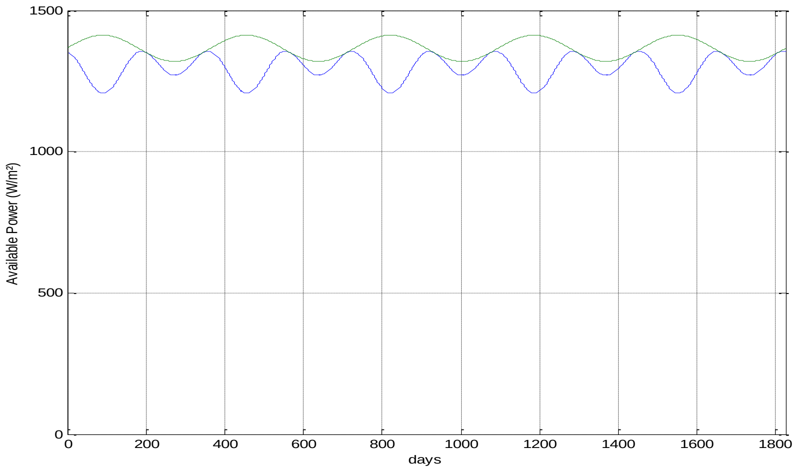
-> Circular orbit of 600 km altitude has been selected among several candidates (out of the scope of this study case, based essentially on payload needs)

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

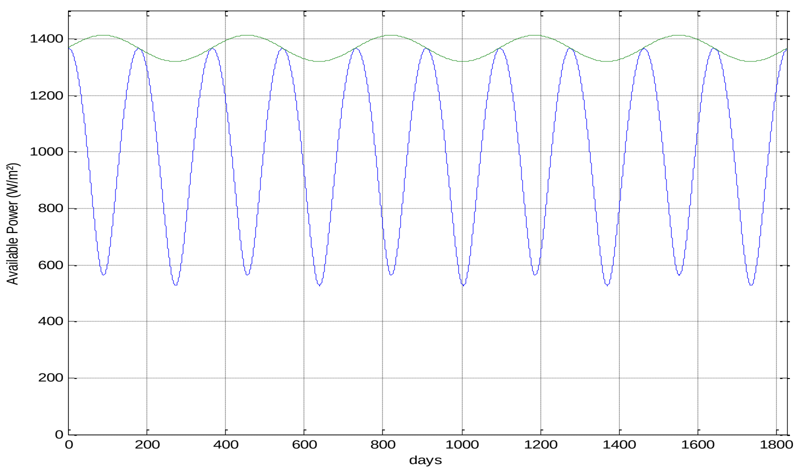
Orbit characteristics		
Average height	600 km	600 km
Period	97 min	97 min
Eccentricity	0.001 (circular orbit)	0.001 (circular orbit)
Inclination	90 ° (polar orbit)	98 ° (sun-synchronous)
Eclipse duration	21.3 min	30 min

Power budget

Orbit selection / Inclination trade-off



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



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

Power budget

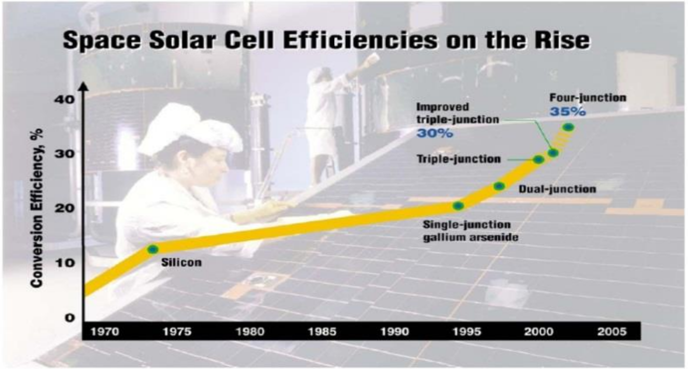
Orbit selection / Inclination trade-off

- 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/m^2)	**1220**	**520**
BOL SA cell efficiency	28 %	
EOL/BOL ratio	76.5 %	
Total available SA power (W / m^2)	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)



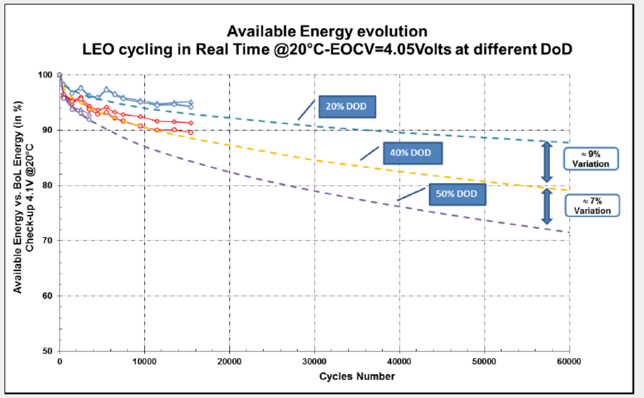
Power budget

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

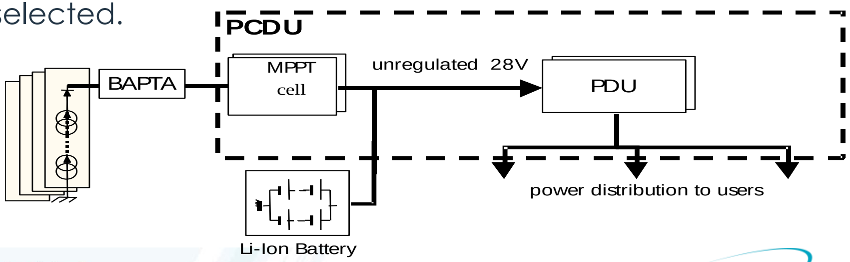
Pout/n – Pout + LL

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.

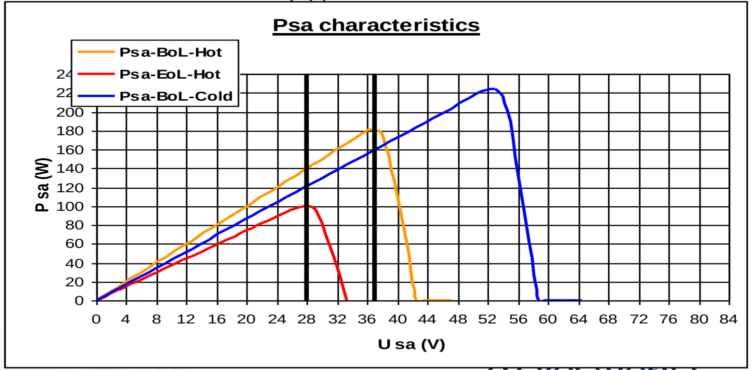


Power budget

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 sunlit duration

Note: Considering 28 V URB with 40 % DoD, battery voltage is comprised between 28 & 37 V in nominal operating cases



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

Agenda

1. Introduction
   - Presentation of Thales Alenia Space Belgium (ETCA)
   - Presentation of myself
   - EPS – general information
2. Primary power sources
   - Solar cells & solar arrays
   - Fuel cells
   - RTG
   - Others
3. Secondary power sources - batteries
4. Power Management, Control & Distribution
   - Architecture
   - PCU / PCDU
5. Power budget – practical exercise
6. **Conclusions**

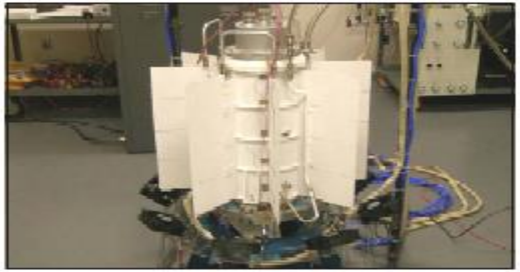
Conclusions

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 [redacted]
- Voltage (28 V, 50 V, 100 V, …)
- Conditioning (S3R, MPPT, …)
- Protections (reliable or not)
- Distribution (fuse, LCL, …)
- …

and shall be adapted nearly on case by case ….



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