

ELECTRICAL POWER SUBSYSTEM FOR THE EUCLID SPACECRAFT

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ABSTRACT

Euclid is the second medium class mission of the European Space Agency in the frame of Cosmic Vision 2015-2025 program [1]. It is a cosmology mission whose prime objective is to study the geometry and the nature of the dark matter and the dark energy with unprecedented accuracy.

The spacecraft will be launched in 2020 by a Soyuz launcher, to perform a six-year survey of the extragalactic sky from a large-amplitude orbit around Lagrange point L2 of the Sun-Earth system.

This paper outlines the Euclid Electrical Power Subsystem (EPS) design, providing a description of the major design drivers and resulting configuration, with a view to highlight aspects that could be considered for future designs.

1. SYSTEM DESCRIPTION

The spacecraft is shown in Fig. 1. It is composed by:

- a Payload Module (PLM) including the Telescope, the baffling system, the Optical Bench supporting the instrument detectors and front ends;
- a Service Module (SVM) comprising the spacecraft platform with its subsystems and the Sunshield protecting the PLM from solar radiation and supporting the PhotoVoltaic Assembly (PVA).

Euclid will produce a massive survey of the extragalactic sky (above 30 deg galactic latitude), simultaneously in the visual band and in the near-infrared band, and a deep survey of two 20 deg² fields observed on a monthly basis.

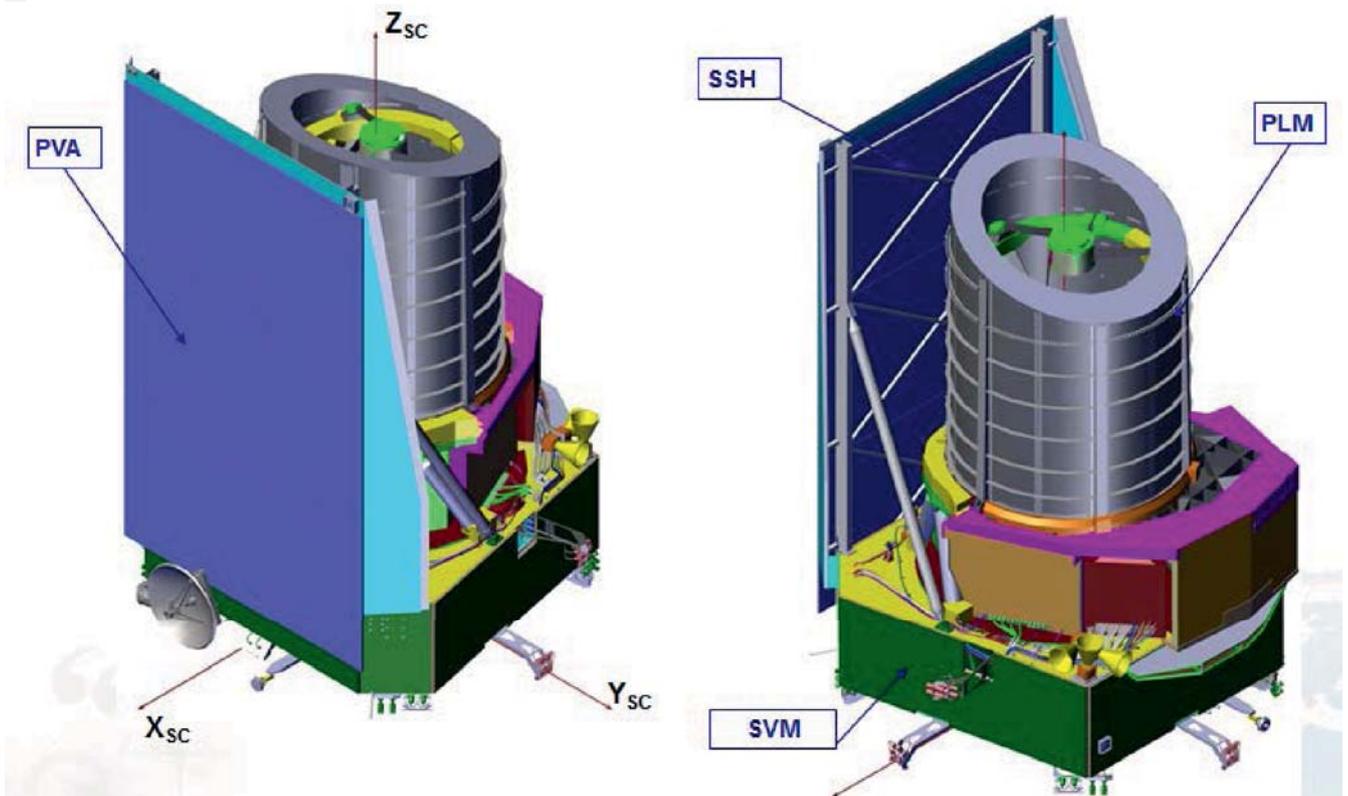


Figure 1. Euclid configuration

The spacecraft will carry two instruments for spectroscopy, imaging and photometry: NISP (Near Infrared Spectro Photometer) and VIS (Visible Instrument); a 1.2 m mirror telescope will focus the incoming images on the focal plane units of these instruments.

The performance of this survey requires an extreme pointing stability associated to the ability to move from one target to the next in few tens of seconds, several thousand of times during the mission without degradation. Stability is the key word of Euclid: stability of the telescope, of the experiment detectors, of the temperatures, of the pointing. A prerequisite for image stability is a near-constant temperature environment, maintained by scanning the sky along circles of near-constant Solar Aspect Angle (SAA). High stability is requested to the structural materials and the temperatures have to be controlled carefully. This constraints had to be taken into account also in the EPS architecture, driving the selection of the Sunshield and solar array characteristics and imposing a high stability of the heater power distribution.

The flight-proven platform architecture of Herschel [2] is taken as reference for the SVM, with six panels and a central cone in which the propellant tanks are mounted. The size of the SVM is scaled to fit the Soyuz launcher (Herschel launcher was Ariane 5 and the SVM had eight panels), but it is also driven by the PLM shape and by the overall dimensions of the Spacecraft. Additional modifications have been introduced to take into account partial obsolescence of the equipment. This architecture allows the modular accommodation of the platform equipment and provides room for the warm payload electronics. Fig. 2 shows the Euclid SVM in closed configuration, while the its exploded view is depicted in Fig. 3.

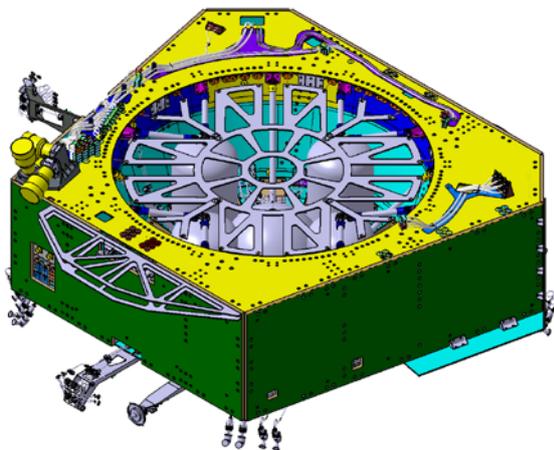


Figure 2. Euclid SVM.

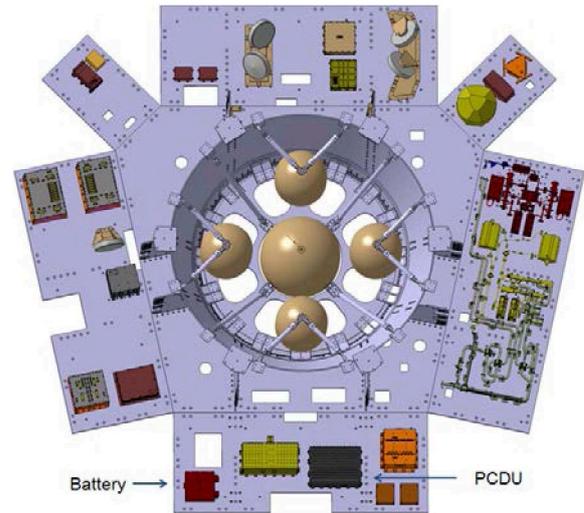


Figure 3. SVM configuration – Exploded view.

The Lagrange point L2 lies approximately on the Earth-Sun line at 1.5×10^6 km from the Earth in the anti-Sun direction. In Euclid nominal attitudes the Sun is in $+X_{SC}$ direction, with elevation angle up to 31° and azimuth angle up to 8° . The lifetime will be 6.25 years, including one month for the transfer phase to the operational orbit around L2.

Thales Alenia Space Italia leads the Euclid industrial team and it is in charge of SVM design, including the electrical power supply chain.

2. ELECTRICAL POWER SUBSYSTEM DESIGN DRIVERS

The spacecraft power demand is up to 1700 W. The EPS is in charge of generating, conditioning, controlling, storing the electrical power and distributing it to instruments and spacecraft equipment. The mission is nominally eclipse free, hence the Battery is designed to be used only during launch phase and in case of attitude anomaly failures, while the Solar Array (SA) is required to generate the electrical power for the whole lifetime. A Power Conditioning and Distribution Unit (PCDU) provides the core of EPS functions and interfaces with the on-board computer for telemetry and telecommands.

The Euclid EPS block diagram is shown in Fig. 4. The power link Battery-PCDU is interrupted at spacecraft skin level for allowing the replacement of the Battery with the battery simulator during the Assembly, Integration and Test (AIT) activities.

The Euclid Power architecture has been built around some major design drivers. In particular, the following aspects have been considered for defining the design.

- Mass saving. In order to avoid a launch mass exceeding the launcher capability, all the trade-offs

- relevant to the EPS had to take into account the contribution of mass.
- Solar Array configuration. The possibility of using a deployable SA was discarded since phase A, due to the requirement of minimising the use of mechanisms: the requirement came from the need of avoiding perturbations. In addition, that option would have caused an impact on mass due to the use of hinges, hold down mechanisms and additional screens between PLM and SA backside. For these reasons, the solution with fixed solar arrays was selected.
- SA power conditioning. At the beginning of phase B2 a trade-off was conducted in order to select the best regulation concept between Maximum Power Point Tracking (MPPT) and Direct Energy Transfer (DET). The characteristics of the mission, with limited variation of illumination (maximum Sun depointing of 33°) and stable array temperature conditions, led to select the DET regulation, in a Sequential Switching Shunt Regulator (S³R) topology.
- Number of shunt sections. Different options were taken into account for defining the number of SA sections most suitable for the EPS. The number of fifteen sections was considered as the optimum for allowing the split of PVA surface in three or five identical panels.

- Regulated vs. Unregulated Power Bus. The eclipse-free characteristics of the Euclid mission would allow avoiding the use of a Battery Charge and Discharge Regulator (BCDR) and the bus maintained regulated by the Battery, under the condition that spacecraft peak power consumption is always lower than the SA power. However, in order to maximize the reuse of equipment from similar missions as Herschel and Planck, a fully regulated 28V_{DC} bus was selected for Euclid as baseline since the definition phase.

3. SOLAR ARRAY

SpaceTech GmbH (DE) is responsible for the Sunshield and Solar Array (SSH) subsystem, with the Photo-Voltaic Assembly (PVA) made by Leonardo (IT), the Solar Panels and Support Structure manufactured by RUAG (CH) and the Thermal Control Hardware manufactured by HPS Ltd. (PT).

The PVA area is close to 11 m². It is located on the central part of the SSH, which size is driven by the PLM shape and limited by the launcher fairing. The environment and the worst case illumination conditions impose additional requirements for the SA sizing:

- the minimum solar flux at summer solstice in L2 is 1293 W/m²;

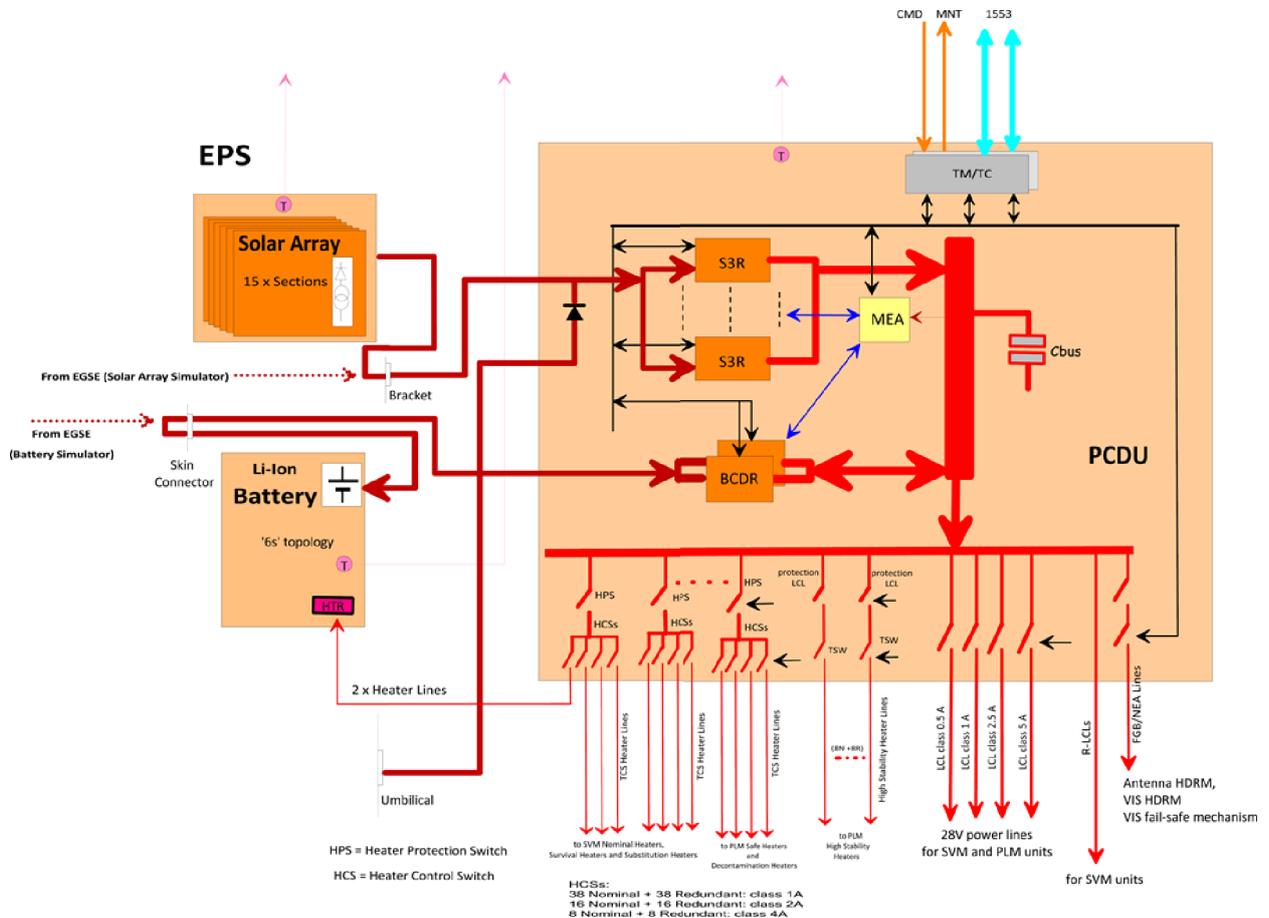


Figure 4: EPS Block Diagram.

- the degradation of the solar cells after six years and three months in L2;
- the maximum sun angle of 121° with respect to the telescope axis and the maximum alpha angle of 8° around X_{SC} axis; adding 1° of tolerance, the resulting incidence on SA will be therefore between 0° and 33° .

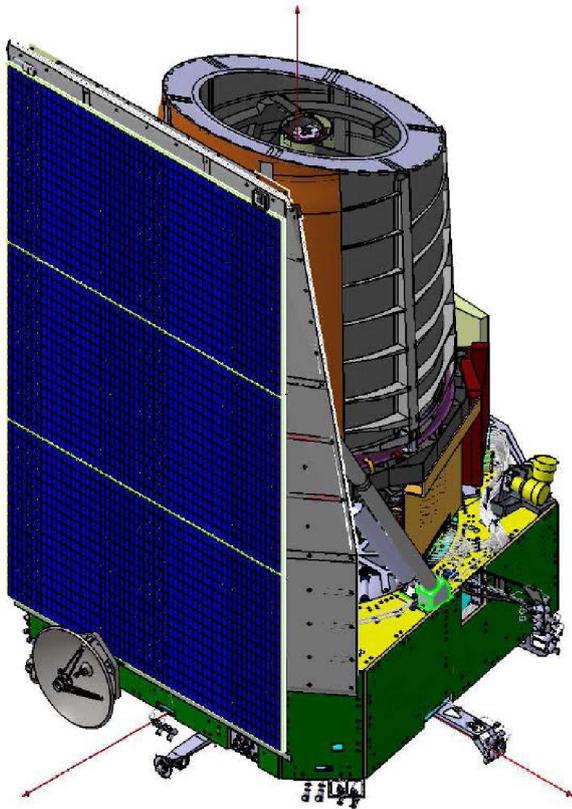


Figure 5. PVA implementation on the spacecraft.

As shown in Fig. 5, the PVA is composed of three panels of the same dimensions and the same cell/string layout. Each panel consists of 51 strings distributed in four sections of ten strings and one section of eleven strings. In total there are fifteen sections. All strings are composed by nineteen solar cells connected in series.

The solar cells used in the PVA are triple junction Gallium Arsenide 3G30C by Azur Space, covered by a $100\mu\text{m}$ CMG coverglass as a protection against solar ultraviolet radiation.

The 3G30C cell has a size of 40×80 mm and two cropped corners. All solar cells shall include a bypass protection diode to prevent the adjacent solar cell from unacceptable high reverse voltages in case of shadowing or cell damage. One option is the internal bypass diode, which is integrated into the cell itself. This diode technology is qualified to a temperature of 140°C and assumed to withstand temperatures up to 150°C for a limited time. As mentioned in the previous section, the telescope and the instruments are extremely sensitive to

temperature and temperature variations: to protect them against thermal radiation, the SSH rear side is covered by Multi-Layer Insulation (MLI) sheets, resulting in high PVA operation temperatures, close to the diode qualification limits. For this reason, the current baseline is to use an external Si bypass diode mounted in one cropped corner of the solar cell: this is the same choice that was made for Herschel and Planck. In that case, the data available from the temperatures measured in flight showed a maximum temperature of 130°C , reached at Winter Solstice with 0° SAA and non-operating solar cells [3]. This bypass diode is performing a specific life test at 195°C in the frame of Euclid PVA qualification. With the mentioned flight and qualification heritage, the selected design is expected to withstand temperatures up to 150°C without any performance degradation.

Each string is terminated by a blocking diode to prevent current flow back and reverse voltages in case of (unexpected) shadowing or failure.

All the harness connecting the PVA parts is redundant, ensuring a robust power transfer concept. The SA sections are connected to the PCDU via power harness. In order to reach a good compromise between mass and voltage losses, an AWG 22 has been selected for power harness.

A set of Sun sensors (FSS and SAS) is accommodated on top of the SSH. These sensors are part of Attitude and Orbit Control Subsystem and connected to the on-board computer.

In order to guarantee a robust design in terms of bonding, isolation and grounding, different technical solutions have been implemented.

The solar array panel cores are connected to the spacecraft structure through bleed resistors integrated into the wiring on the back side of the panels. In order to comply with the redundancy concept, two bleed resistors per panel are implemented.

The complete SSH structure and the sensor brackets are referenced to the spacecraft potential. The insulation between the interface points of the structure and the solar array panels is achieved by means of Glass Fibre Reinforced Plastic (GFRP) brackets.

A double insulation concept has been applied for all the front and rear side components in order that, even after a single failure, the elements are still insulated each other. Apart from the standard measures, on the panel rear side the electrical components have been covered with Kapton foil. This configuration has been adopted to avoid the risk of electrical contact between the rear side metallic parts (e.g. bleed resistors, blocking diode terminals) and the MLI internal layers, which are grounded to the spacecraft.

The MLI external layer (facing the panel substrate) is

made by uncoated Kapton foils, in order to guarantee the double insulation concept described above. The other MLI layers are electrically interconnected and bonded to the grounding rail by means of bonding straps. This grounding rail is connected to the spacecraft voltage reference. Fig. 6 provides an overall scheme of the grounding and isolation concept.

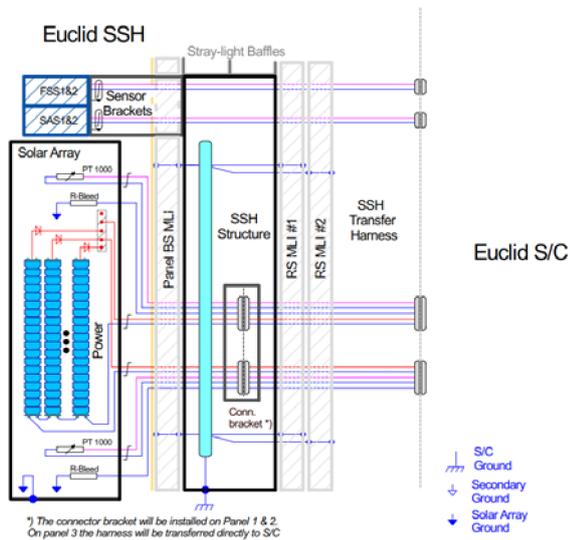


Figure 6. SSH bonding and grounding philosophy

The implemented grounding concept avoids the build-up of electric charges on solar panels. Furthermore, it ensures that the involved equipment (structure and Thermal Control Hardware) is connected to the spacecraft reference with low resistive paths.

As characteristic of the sequential shunt switch regulation, the number of SA sections which are connected by the PCDU to the power bus depends on the spacecraft power demand. As shown in Fig. 7, the sections have been arranged in order that the ones facing the most sensible PLM area will be always connected during the science operations: this configuration ensures a lower and stable temperature in the area with higher radiative coupling between SSH and PLM.

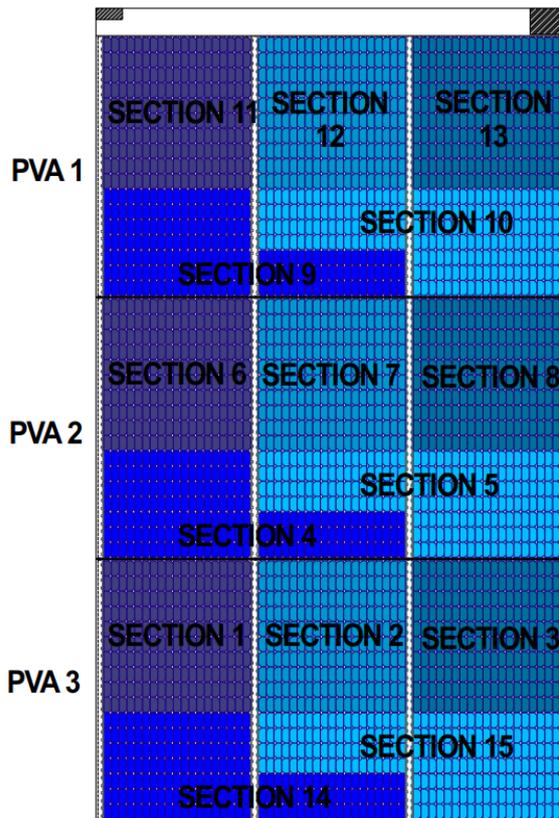


Figure 7. SA sections configuration

In view of maximum decoupling between high temperature solar panels and instruments, further features have been implemented in the SSH thermal design. As shown in Fig. 8, a multiple MLI-stack installed on the back side of the SSH central part allows a minimized heat flux from the (PVA) panel rear side towards the PLM, as the three MLI stacks have defined intermediate spaces to radiate also laterally.

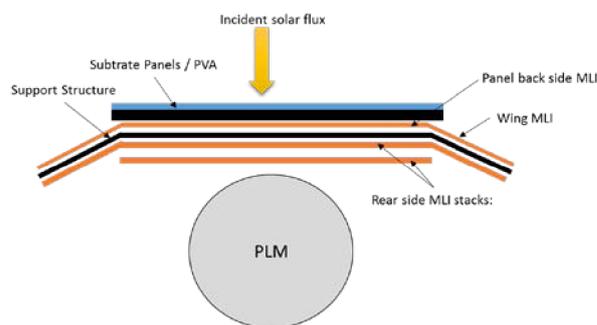


Figure 8. SSH MLI design (schematic illustration)

The selected configuration with nineteen 3G30C cells in series guarantees a stable working condition under different temperature cases, as shown in Fig. 9.

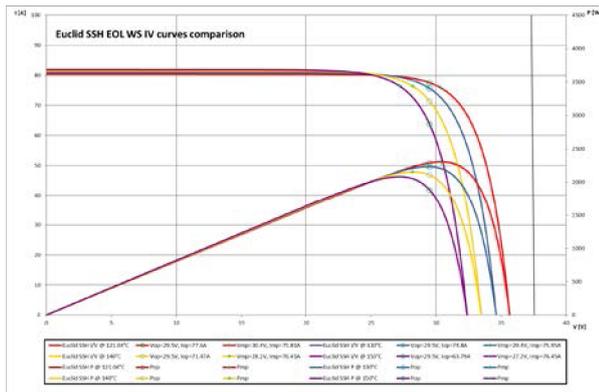


Figure 9. SA curves vs. temperature

According to the thermal analysis, the expected maximum temperature on shunted SA sections is 137°C at L2 and, as described previously, the maximum temperature measured on Herschel and Planck was lower than 130°C. Under these extreme conditions, the SA operating voltage (V_{op}) might exceed the maximum power point voltage (V_{mpp}) but, once the SA sections are connected to the power bus, the temperature decreases and a self-recovery is ensured, with V_{op} on the left side in the SA curve ($V_{op} < V_{mpp}$).

Two temperature sensors (PT1000) are installed on each panel in order to monitor the substrate rear side temperature. These sensors are connected to the on-board computer.

The Power generated by the SA during the mission is between 1750 W and 2450 W, depending on SAA, solar flux and ageing.

4. BATTERY

The Battery is made by Saft (FR). It is composed of VES16 Li-Ion cells developed by Saft, arranged in 6s-6p topology.

VES16 cell has been qualified in 2011 in the frame of a contract with CNES [4]. It is a D-size Li-Ion cell with 4.5Ah capacity, initially dedicated to both Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO) programs, which utilization can be extended to other space missions. Its electrochemistry is based on Saft heritage on high capacity cells for space application, tailored for a cell with smaller capacity. The main cell characteristics are depicted in Fig. 10.

The arrangement of the cells in Euclid battery is done in a single deck version: this is one of the configurations qualified in the frame of ESA's General Support Technology Programme #5.2 (GSTP-5.2) activity [5]. It consists of a parallel wiring of six strings, each one composed of six cells in series. The cells are glued by resin between the baseplate and the top plate.

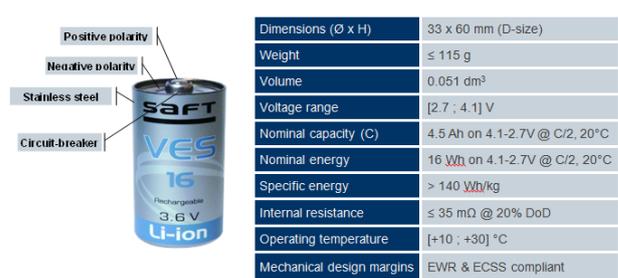


Figure 10. VES16 Battery cell

A Simplified Balancing System (SBS) is implemented on the terminals of each individual cell. The principle of this balancing electronics system is based on cell current consumption above a given voltage threshold. The system is fully autonomous, i.e. it does not need to be commanded/monitored by the PCDU. The SBS architecture is based on a simple circuitry with a core micro shunt associated to a set of resistors, in order to adjust the threshold at which the balancing function is activated

The serial connection of the cells in a string and the SBS is implemented with an equipped printed circuit board (PCB). This PCB provides also the access for cell voltage monitoring.

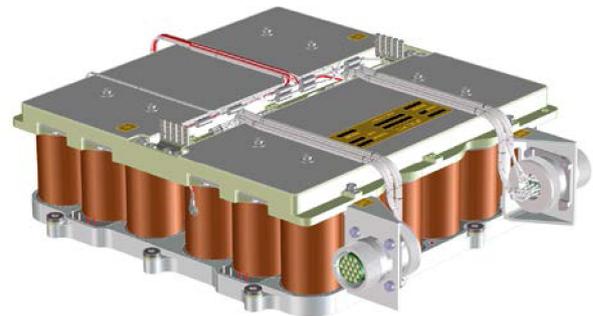


Figure 11. Euclid battery general view

Euclid is nominally an eclipse-free mission and therefore the Battery is nominally used during Launch and Early Orbit Phase (LEOP) only. Contingency cases might imply the use of the Battery in case of attitude loss or to cover any peak power demand from the spacecraft. The sizing case is represented by the energy required by the spacecraft from lift-off until few minutes after the separation.

The Battery has been specified to sustain one hundred cycles for all the mission duration, considering an average power discharge of 300W for seventy minutes, including a peak power discharge of 850W lasting ten minutes at each cycle, in the temperature range 10°C to 20°C.

In order to evaluate the impact of micro-cycles on electrical performances, three VES16 cells are subjected to an accelerated life-test (discharge at 4W for five minutes at 10°C, for several thousand cycles). At the time of the issue of this paper the test is still running in

the European Space Battery Test Centre at Estec.

The Euclid battery has a nameplate energy of 576 Wh: this size allows to cover the worst case duration of launch with a Depth Of Discharge (DoD) lower than 50%.

Even if Euclid battery presents a design coming from GSTP-5 battery range, the size difference regarding GSTP-5 Qualification Models (QM) and the specific electrical design to insure high discharge current (52.5A during pulse) justify its classification in Category C.

Then, in addition of electrical, thermal and mechanical analysis performed, Saft is manufacturing two battery models:

- one Structural and Thermal Model (STM) dedicated to simulate thermally the battery dissipation during different phases, by the use of specific heater bands. This battery is mechanically representative of Flight Model (FM);
- one Engineering Qualification Model (EQM) which aims to qualify the battery to Euclid requirements.

The qualification and space mission of this battery will extend VES16 battery range and will give more heritage to Saft for cosmology missions.

5. POWER CONTROL AND DISTRIBUTION UNIT

Terma (DK) manufactures the Power Control and Distribution Unit (PCDU).

The main functions required to the PCDU are to generate and distribute a single, fully regulated bus of 28V_{DC} with a 1700 W (average) and 2200 W (peak) power capability in sunlight mode and 400W power capability during eclipse.

To meet its functional requirements, the PCDU is required to include the following elements:

- a three-domain regulation working in majority voting control;
- a bus capacitor bank;
- fifteen Single Point Failure Free Sequential Switching Shunt Regulator (SS3R) modules;
- two Battery Charge and Discharge Regulator (BCDR) modules;
- sixty-eight Latching Current Limiters (LCL) and six Re-triggerable Latching Current Limiters (R-LCL), with different current limitation capabilities;
- 144 heater lines
- three Non-Explosive device Actuators (NEA) and three Frangibolt actuators
- Two Command and Monitoring modules, including Mil-Std-1553 Remote Terminal interfaces.

The PCDU block diagram is shown in Fig. 4.

The PCDU manages the SA power and the battery

power to provide a regulated 28V \pm 0.5% Main Bus.

A Main Error Amplifier (MEA) function manages the power regulation such that the 28V bus supply will always be provided when sufficient energy is available, either from SA, from the Battery or from both. Three independent error amplifiers are voted into one reliable MEA line that regulates the shunts, the battery charging and battery discharging in a classical three-domain regulation scheme. Each error amplifier is voted together by means of standard 2/3 majority voting circuitry forming the reliable MEA control line. The MEA line is distributed reliably to all power regulators.

The PCDU will always use SA power for Main Bus regulation as long as sufficient power can be derived for the applied main bus load. Otherwise, the remaining power required will be provided from the battery.

The PCDU does not include software for any power management function. The transitions between the three domains are automatic and lead to negligible transients to the main bus voltage.

The SA power conditioning is performed by fifteen SS3Rs. Each shunt is connected to a SA section and it is required to regulate up to 7A. The architecture is such that no single failure can lead to the loss of a SA section. The excess SA power, not needed to satisfy the main bus and the battery charge, will be dissipated on the SA (i.e. shunted) and only a minor fraction is dissipated in the PCDU. Three SS3Rs include also an EGSE interface in order to power the spacecraft via umbilical lines during the ground testing.

The battery charge regulators (BCR) and the battery discharge regulators (BDR) manage the battery charging and discharging according to available power and battery power.

BCR and BDR functionalities are implemented on the same BCDR module. For ensuring a redundant configuration the PCDU is equipped with two BCDR modules operating in parallel. Each BDR can sustain the power needed to supply the spacecraft at launch.

A capacitor bank is foreseen at main bus level in order to:

- stabilise the bus voltage regulation loop
- ensure a low output impedance
- filter the switching noises due to the regulation.

The PCDU provides seventy-four LCL outlets to protect the users/loads. The LCLs are divided in five different classes, with different limitation capabilities. All the LCLs can be switched-on/off by 1553 commands, with the exception of six R-LCLs, devoted to critical loads, which cannot be switched OFF and automatically attempt to switch ON when powered or after a retrigger interval when a trip off event occurred. Part of the LCLs are directly commandable via High Power Command. Some LCLs are required to be configured as "ON-

Protected”, i.e. no single failure can lead to have an LCL which cannot be switched OFF. All LCLs have an under-voltage lockout function that ensures switch-off in case of main bus under-voltage.

The on-board computer is in charge of the SVM and PLM thermal control, but the heaters actuations pass through the PCDU. Each heater line can be individually actuated. To avoid permanent supply of an heater due to switch failure or heater-structure contact, a second serial switch is implemented. Heaters are grouped up to a maximum of eight to reduce the number of these switches.

The status of the switches and the current of each heater group is monitored via telemetry. In addition to these, sixteen high stability heaters are requested from the PLM thermal control. They are implemented with high output voltage stability.

6. CONCLUSIONS

This paper presented the Euclid EPS, describing the major design drivers, the architecture and the characteristics of the equipment.

The Euclid System Preliminary Review (PDR) has been successfully completed in 2015 and the program is in its phase C. At the present time, all the power equipment PDR's have been completed, while the relevant Critical Design Reviews are under preparation. The outcomes of the detailed design phases have been presented: analyses and test results up to the issue of this paper are promising.

7. REFERENCES

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