ELECTRONICS DIVISION

LEONARDO

Solar Cell Interconnector Design Optimization for Surviving Harsh Fatigue Environments

ESA Contract 4000114789/15/NL/FE

Final Presentation

08-06-2021

Summary

> Scope of Program
> Task 1: Mechanical Design and Analysis
> Task 2: Manufacturing
> Task 3: Testing and results
> Conclusions
> Lessons Learnt
> Future developments

Scope of Program

Main goal: to develop new interconnect design solutions able to withstand several thousands of thermal cycles in a wide range of missions environments

Interconnected cells

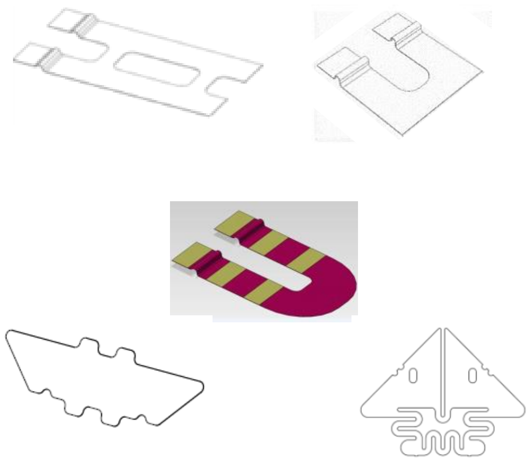
Trend: Satellites lifetime increasing → Number of thermal cycles increasing

→ Interconnects must ensure reliability and survive to thermo-mechanical fatigue

Cross section schematics showing interconnect function

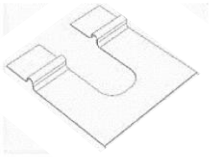
Task 1: Mechanical Design and Analysis

Leonardo heritage for interconnect technologies

I/C TYPEs	SHAPEs	MATERIAL/SURFACE FINISH/ CONNECTIONs	REPRESENTATIVE PICTUREs
Front/rear – rear/BB Front/rear Rear-rear	U; C; 2H Bat; Spade	Ag/-/sold. Ag/-/weld Molybden/Ag-sputtered/sold. Molybden/Ag-sputtering/weld Invar/Ag/sold. Invar/Ag/weld Au/-/weld Ag/Au/weld. Invar/Au/weld Invar/Au economic/weld	

Baseline:

C-shaped, Ag-plated Invar, for front-rear and rear-rear connections



«Spade» shaped, Ag-plated Invar, for rear-rear connections in case of single coverglass

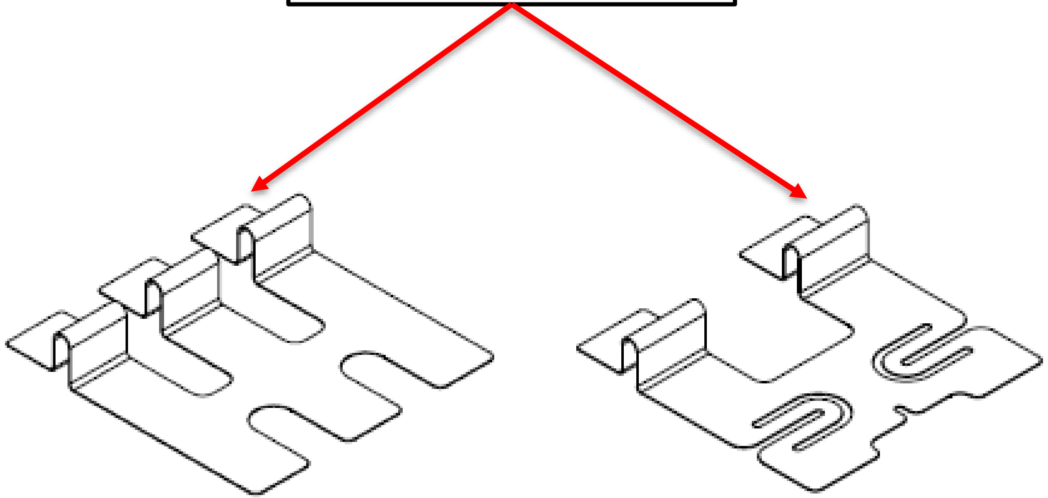
Task 1: Mechanical Design and Analysis

Core Material selection

From Invar: Iron (64%), Nickel (36%) alloy

To Rodar: Iron, Nickel (29%) and Cobalt (17%) alloy

Geometry definition



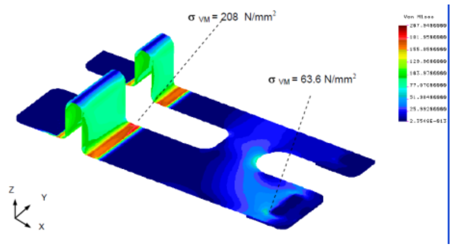
Trident
(sometimes indicated as triple leads)

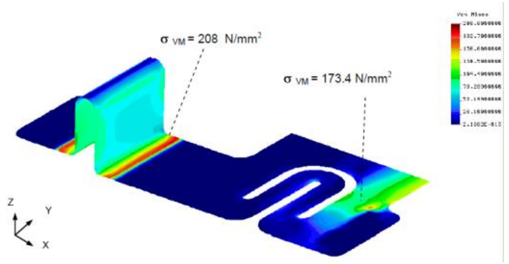
Bifidus

By design iteration, LND has developed 2 new interconnects design, Trident and Bifidus, aimed to introduce advantages in terms of PVA manufacturing and reliability

Task 1: Mechanical Design and Analysis

- The Rodar material shows higher rigidity with respect to the Invar→ improved string manufacturing thanks to better handling
- The extended loop permits to better absorb the out of plane stresses and to reach a greater fatigue strength → Number of cycles achievable is $N > 10^6$
- The Triple lead I/C shows good stress distribution on the loop and in the welding areas;
- Triple lead I/C reduces number of welding joints → 6 welding joints vs 8 needed for 'C' shaped Invar interconnect (-25% reduction)
- The Bifidus I/C shows a good behavior under stress in the loop area, less around the welding joints, but acceptable.
- Symmetrical alternating stresses were analysed to be, on both trident and bifidus designs, 60% lower with respect to those simulated on C-type Invar interconnects



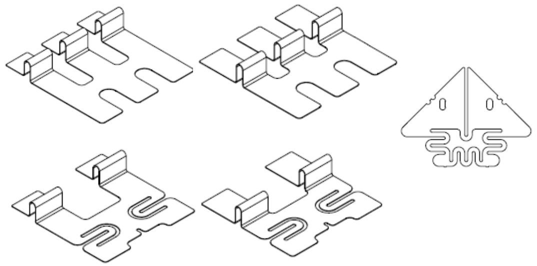


FEM analysis examples

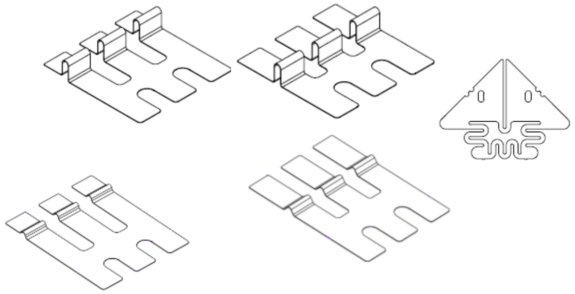
Task 2: Manufacturing and preliminary Design verification

Interconnects Manufactured

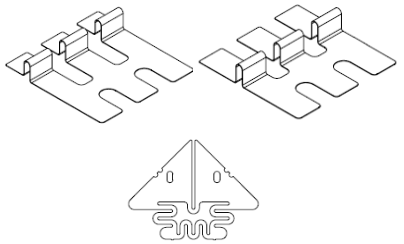
Ag plated Rodar



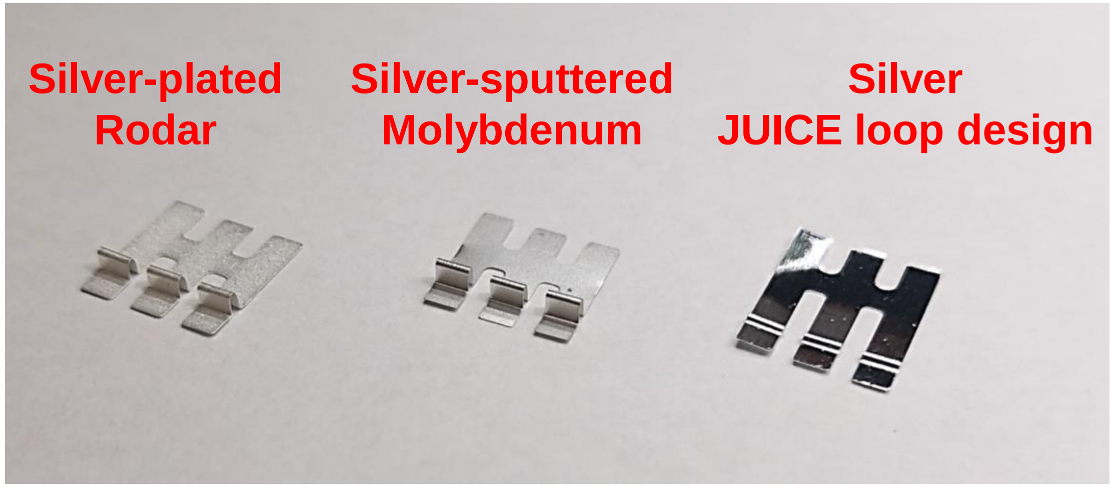
Silver



Ag sputtered Molybdenum



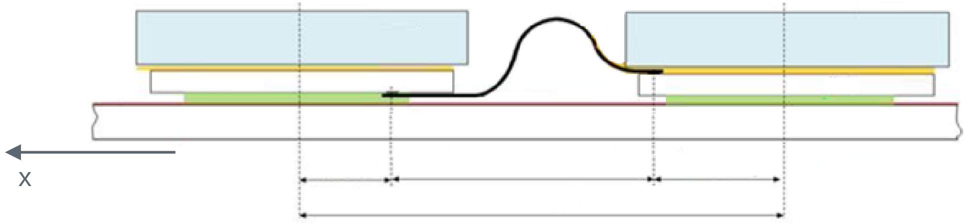
Picture of Trident interconnects manufactured with 3 different materials



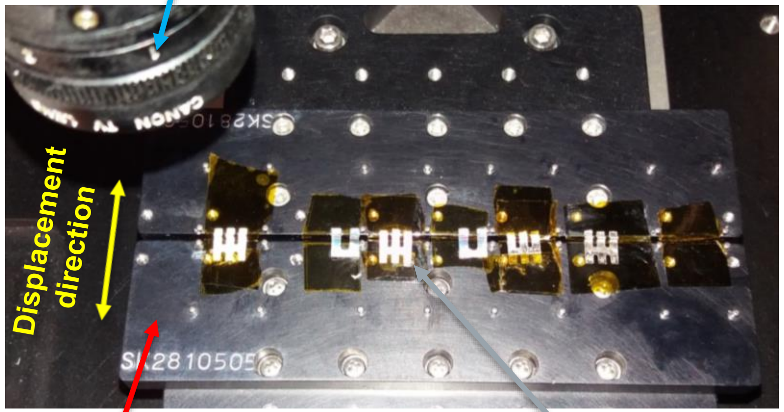
Task 2: Manufacturing and preliminary Design verification

As confidence test, all interconnects (Rodar, Molybdenum, Silver) have been submitted to flex test at ambient temperature

Interconnects displacements have been computed for various temperature cases→ contraction for cold cases, expansion for hot cases



Equivalent displacement achieved by means of piezo electric actuator



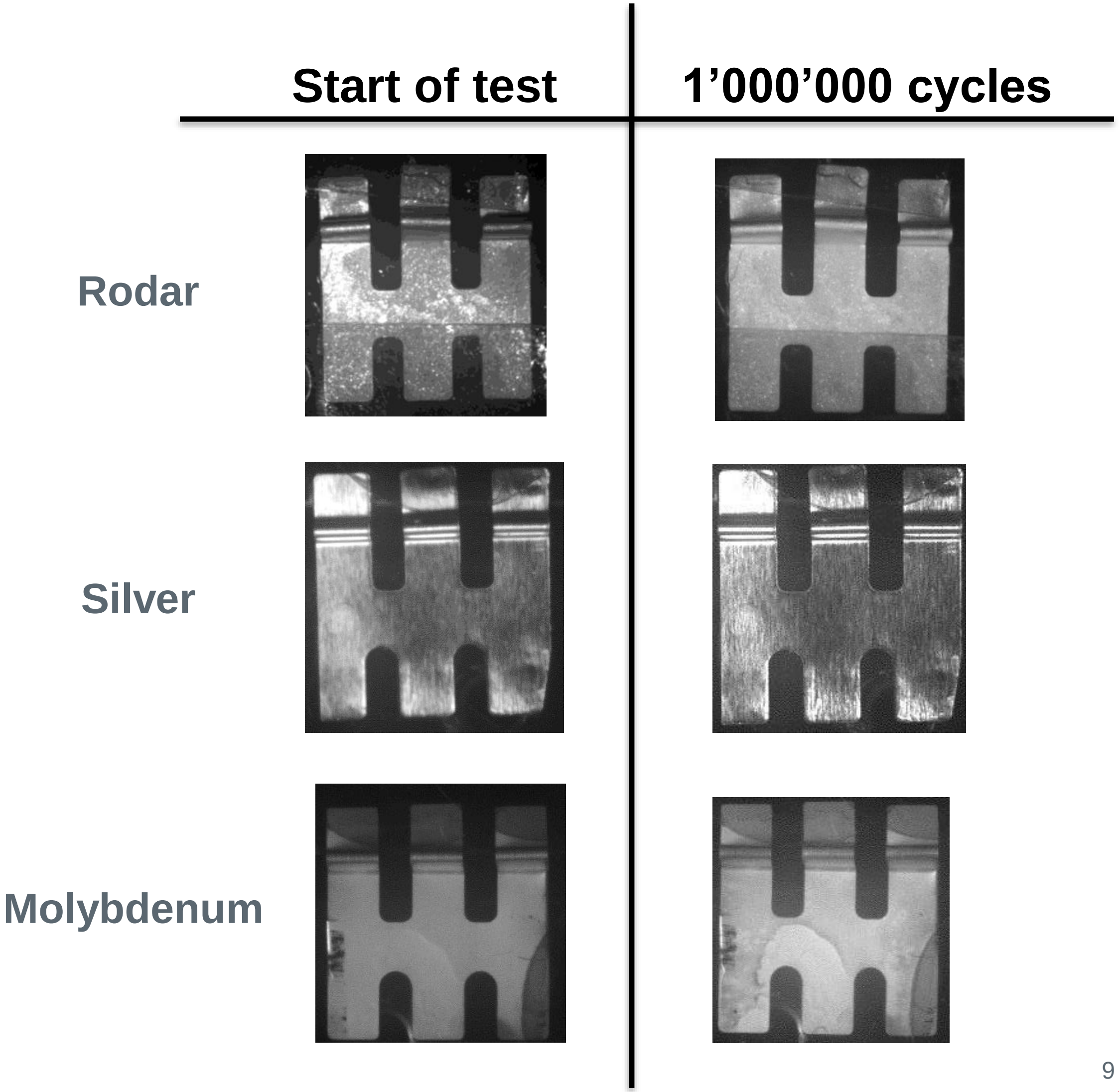
Task 2: Manufacturing and preliminary Design verification

Flex Tests results

- A large number of displacement cycles have been performed in order to stress the relief loops on interconnects
- 16 interconnects samples tested

All interconnects survived to > 1 M cycles without cracks

When artificially introduced, cracks did not evolve significantly in 1 M cycles



Task 3: DVTs manufacturing

7 DVTs manufactured as result of different permutations

Interconnect Geometries

- Triple leads
- Bifidus

Substrate Supplier

- Airborne
- Thales

Interconnect Materials

- Ag plated Rodar
- Ag sputtered Molybdenum
- Silver

Solar cells typologies

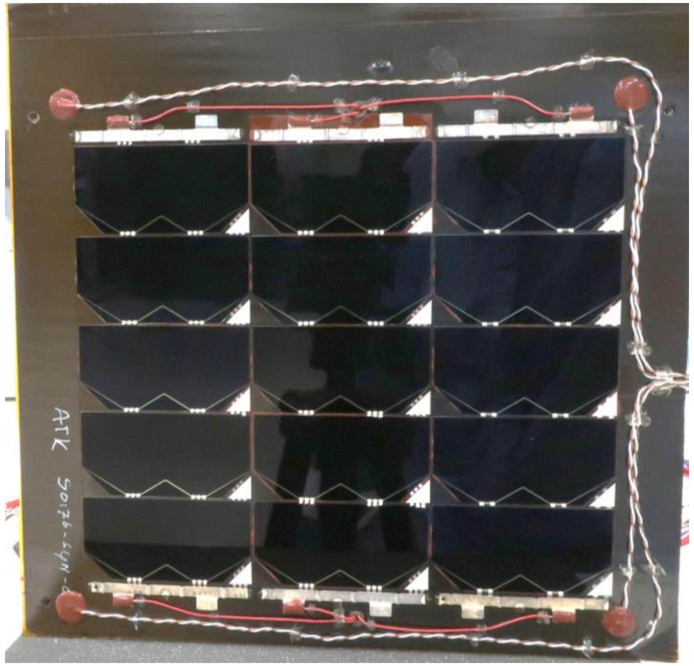
- 3G28 4x8 cm^2 size
- 3G30 4x8 cm^2 size
- 3G30 6x12 cm^2 size

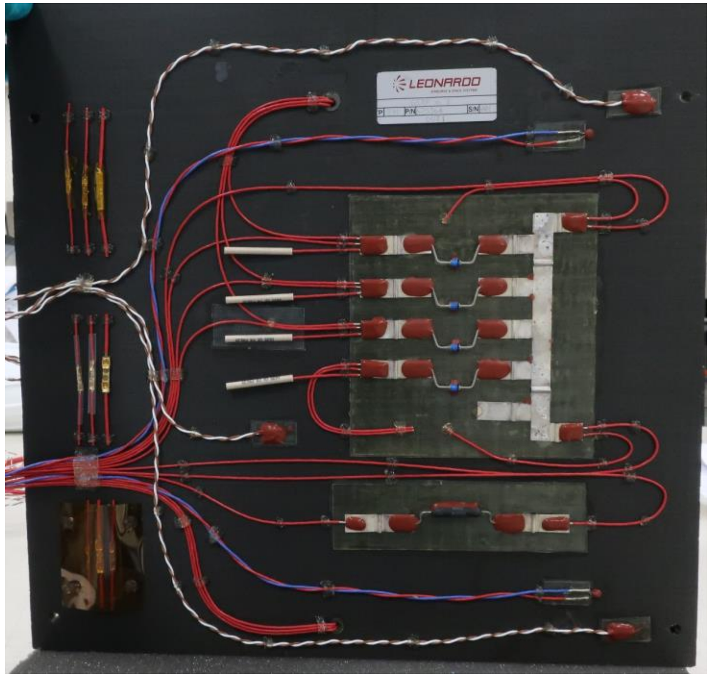
Thermal cycling Profile

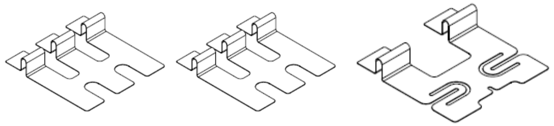
- Low Earth Orbit
- Geostationary Orbit

DVT 1: Triple leads and Bifidus Rodar Interconnects

Description	DVT1	
Environment	**Extended LEO** (100k cycles, -110/+110 °C)	
Coupon size	25x30cm^2	
Substrate supplier	Airborne	
Lay-out	15 cells in total	
N° of strings	2 Strings	1 String
Bare Cell	**3G30C 40x80 mm^2, 150µm**	
Cell Front Interconnector	**Ag Rodar three leads**	**Ag Rodar bifidus**
Bypass diode	Ext. Silicon diode	
By-pass diode front I/C	Ag Rodar three leads	Ag Rodar bifidus
By-pass diode rear I/C	Ag Rodar three leads	Ag Rodar bifidus
Cell Rear Interconnector	Ag Rodar three leads	Ag Rodar bifidus
Bus Bar	Ag Invar	
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires	



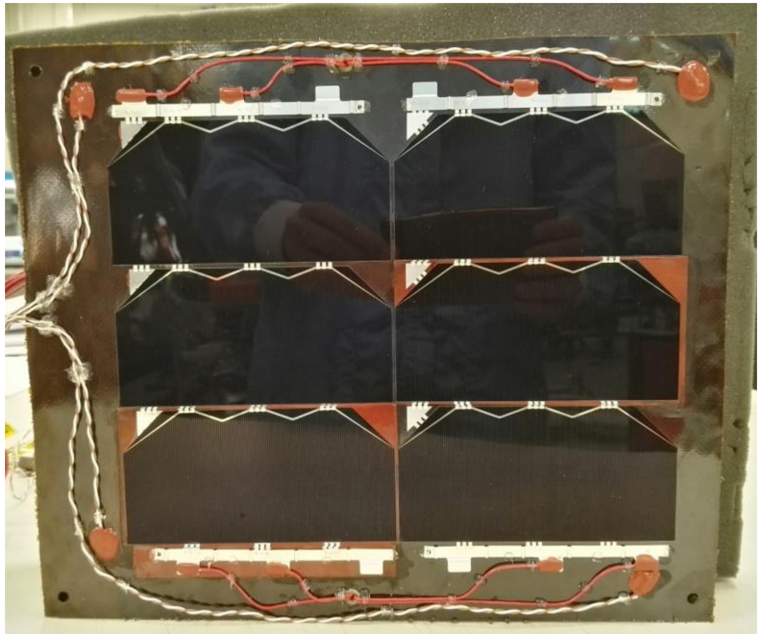


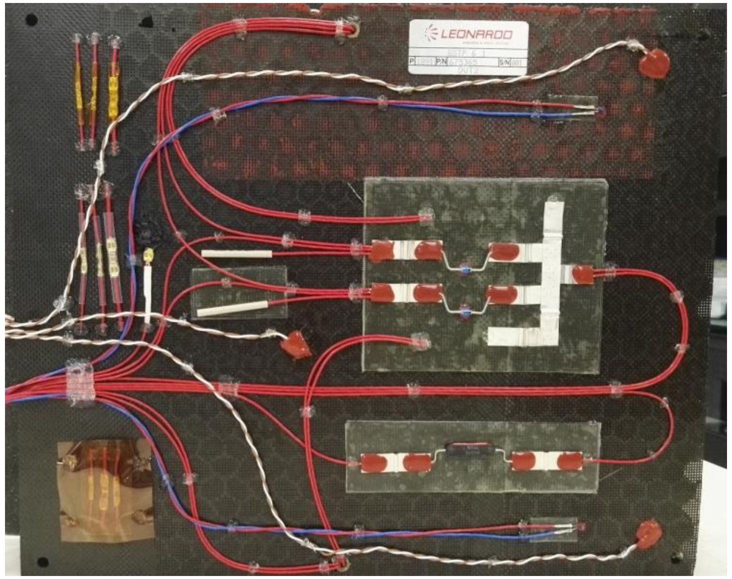


Rodar

DVT 2: Triple leads Molybdenum Interconnects

Description	DVT 2	
Environment	**Extended LEO** (100k cycles, -110/+110 °C)	
Coupon size	25x30cm²	
Substrate supplier	Airborne	
Lay-out	6 cells in total	
N° of strings	1 String	1 String
Bare Cell	**3G30C 60x120 mm², 150µm**	
Cell Front Interconnector	**Ag Molibdenum three leads**	
Bypass diode	Ext. Silicon diode	
By-pass diode front I/C	Ag Molibdenum three leads	
By-pass diode rear I/C	Ag Molibdenum three leads	Ag Molibdenum spade
Cell Rear Interconnector	Ag Molibdenum three leads	
Bus Bar	Ag Molibdenum	
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires	

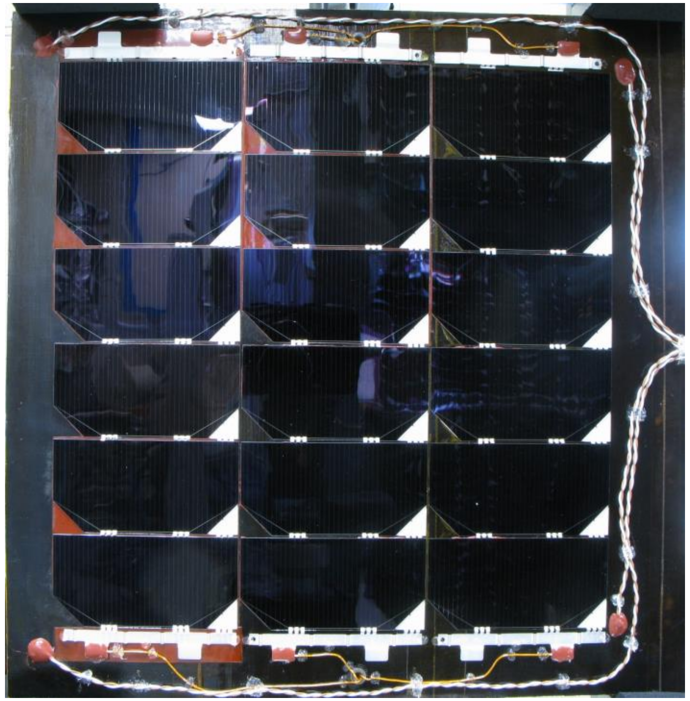


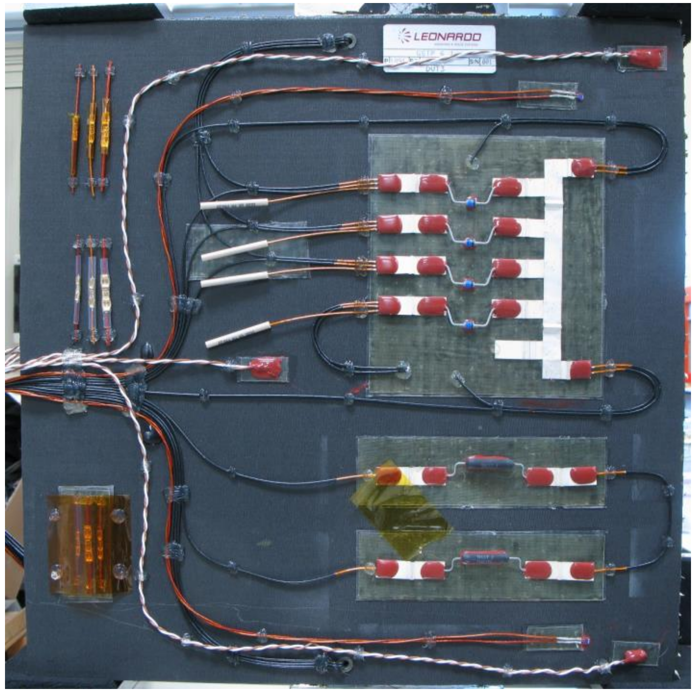


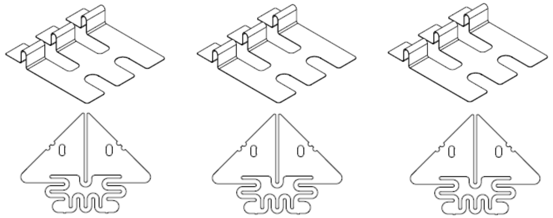
Molybdenum

DVT 3: Triple leads Molybdenum Interconnects

Description	DVT 3
Environment	**GEO** (2100 cycles, -175/+135 °C)
Coupon size	30x30cm^2
Substrate supplier	Airborne
Lay-out	18 cells in total
N° of strings	3 strings
Bare Cell	**3G28C 40x80 mm2, 100µm (JUICE thin cells)**
Cell Front Interconnector	**Ag Molibdenum three leads**
Bypass diode	Ext. Silicon diode
By-pass diode front I/C	Ag Molibdenum three leads
By-pass diode rear I/C	Ag Molibdenum spade
Cell Rear Interconnector	Ag Molibdenum three leads
Bus Bar	Ag Molibdenum
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires Antistatic AWG 24 wires



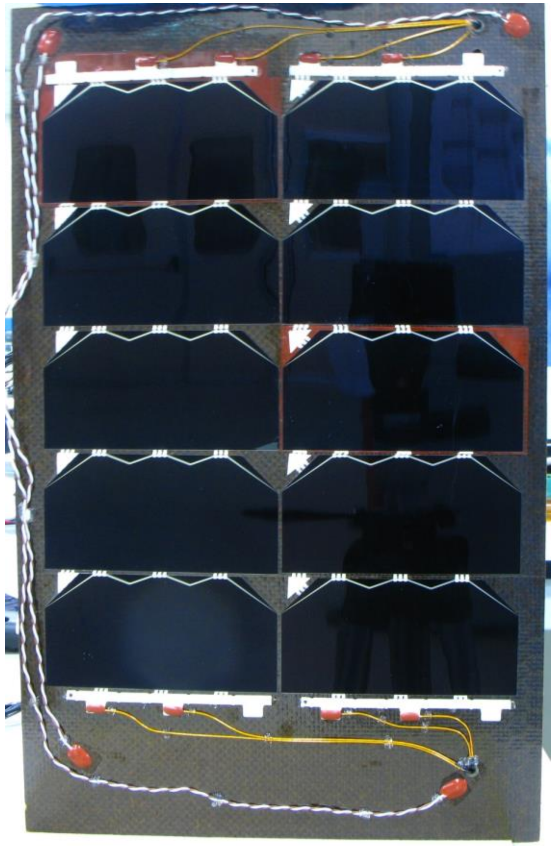


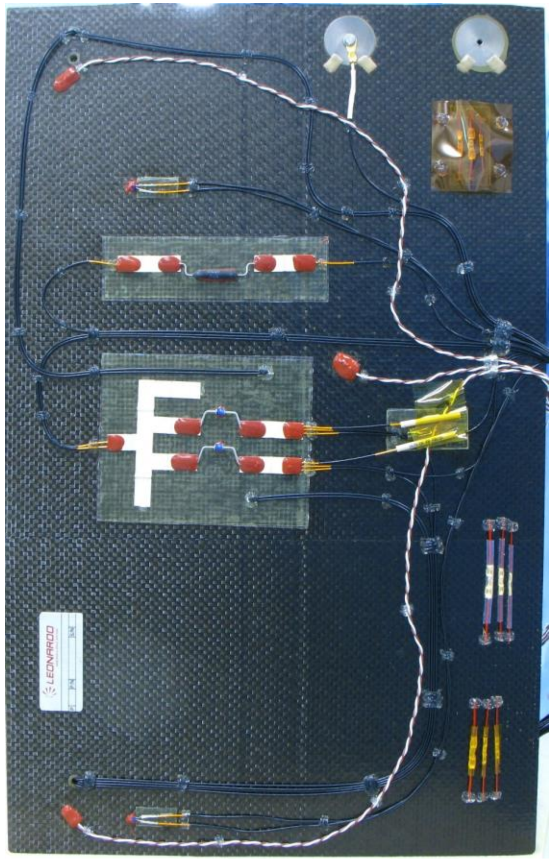


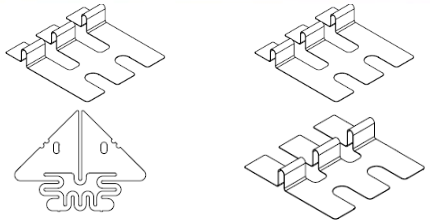
Molybdenum

DVT 4: Triple leads Rodar Interconnects

Description	DVT 4	
Environment	**GEO** (2100 cycles, -175/+135 °C)	
Coupon size	35x35cm^2	
Substrate supplier	Thales	
Lay-out	10 cells in total	
N° of strings	1 String	1 String
Bare Cell	**3G30C 60x120 mm^2, 150µm**	
Cell Front Interconnector	**Ag Rodar three leads**	
Bypass diode	Ext. Silicon diode	
By-pass diode front I/C	Ag Rodar three leads	
By-pass diode rear I/C	Ag Rodar three leads	Ag Rodar spade
Cell Rear Interconnector	Ag Rodar three leads	
Bus Bar	Ag Invar	
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires Antistatic AWG 24 wires	



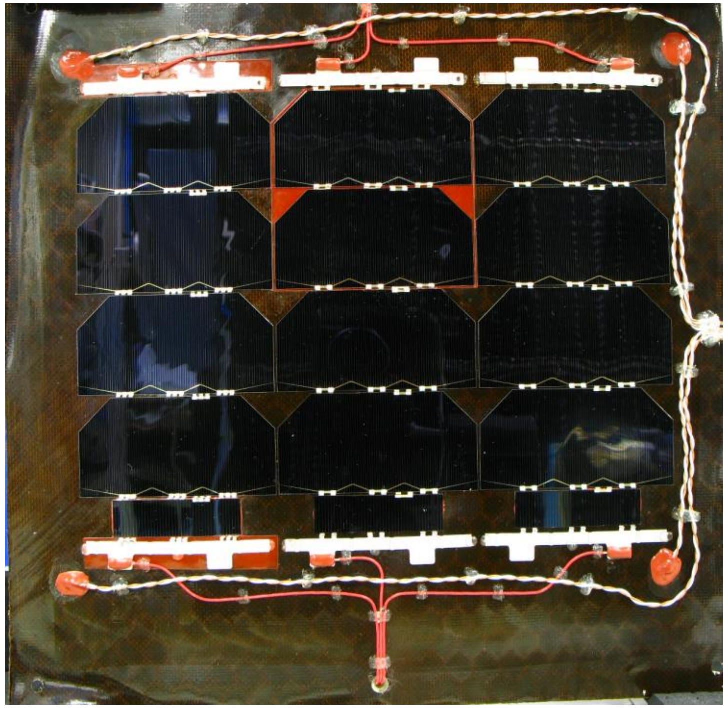


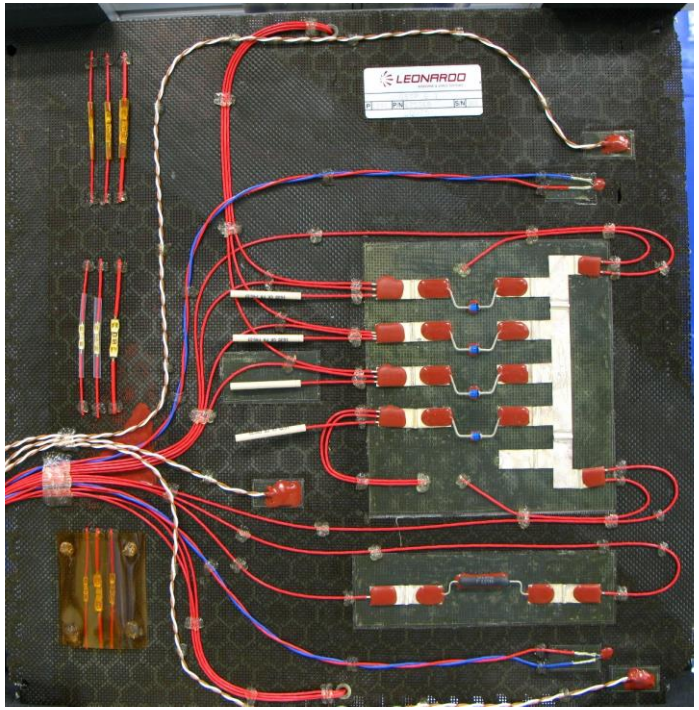


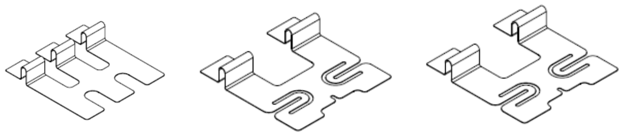
Rodar

DVT 5: Triple leads and Bifidus Rodar Interconnects

Description	DVT 5	
Environment	**Extended LEO** (100k cycles, -110/+110 °C)	
Coupon size	25x30cm^2	
Substrate supplier	Thales	
Lay-out	12 cells in total	
N° of strings	1 Strings	2 String
Bare Cell	**3G30C 40x80 mm^2, 150µm**	
Cell Front Interconnector	**Ag Rodar three leads**	**Ag Rodar bifidus**
Bypass diode	Integrated diode	
By-pass diode front I/C	Ag Rodar three leads	Ag Rodar bifidus
By-pass diode rear I/C	-	-
Cell Rear Interconnector	Ag Rodar three leads	Ag Rodar bifidus
Bus Bar	Ag Invar	
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires	



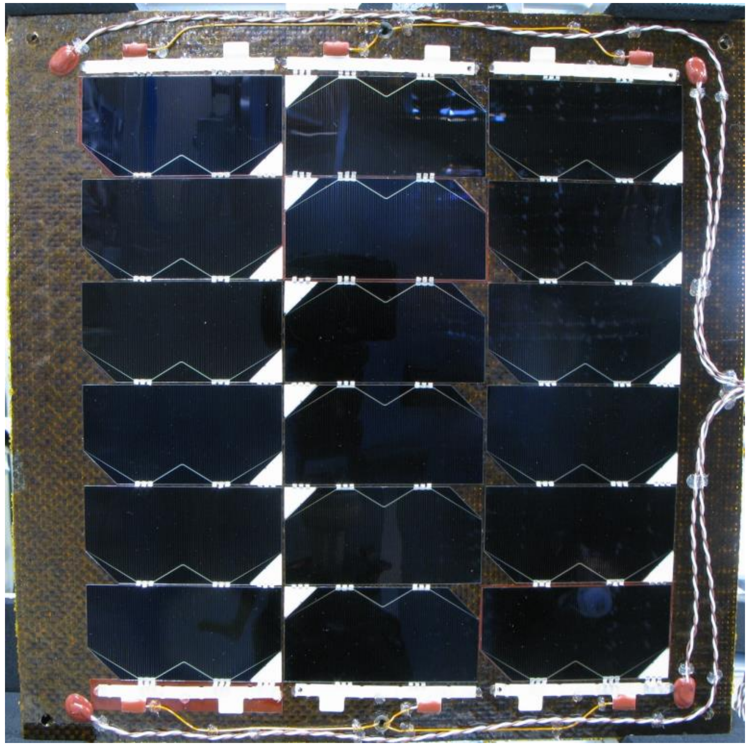


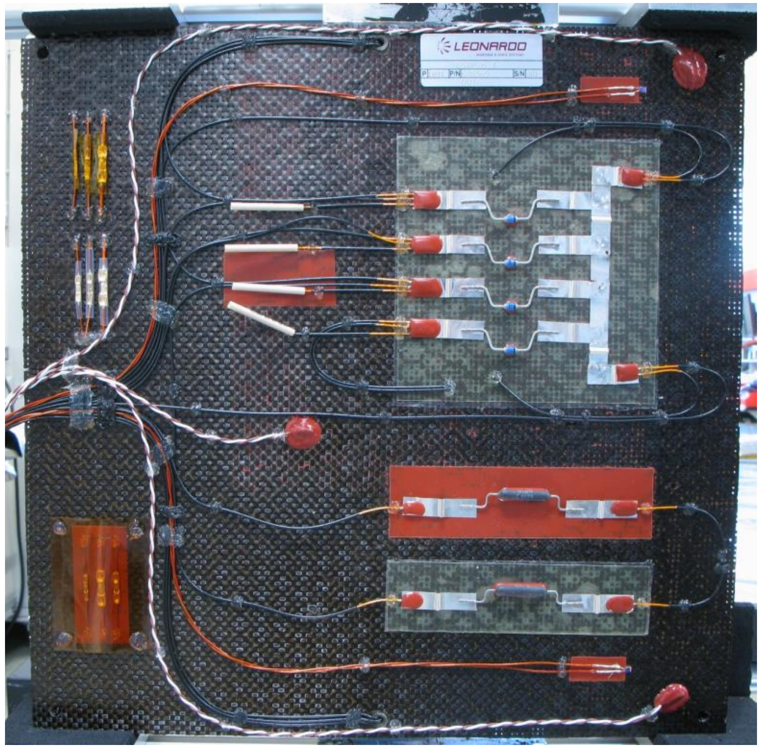


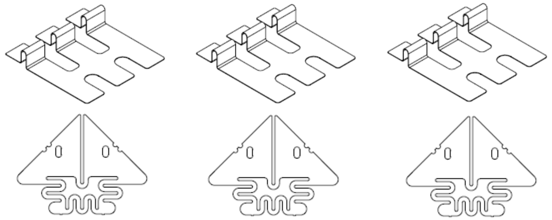
Rodar

DVT 6: Triple leads Silver Interconnects

Description	DVT 6
Environment	**GEO** (2100 cycles, -175/+135 °C)
Coupon size	30x30cm^2
Substrate supplier	Thales
Lay-out	18 cells in total
N° of strings	3 strings
Bare Cell	**3G30C 40x80 mm2, 150µm**
Cell Front Interconnector	**Ag three leads**
Bypass diode	Ext. Silicon diode
By-pass diode front I/C	Ag three leads
By-pass diode rear I/C	Ag spade
Cell Rear Interconnector	Ag three leads
Bus Bar	Ag
Rear side elements	JANTXV1N5418 blocking diodes RWR71S1002FR resistors M222 thermistors SPM AWG 20/24/26 wires Antistatic AWG 24 wires







Silver

DVT 7: Triple leads Silver Interconnects

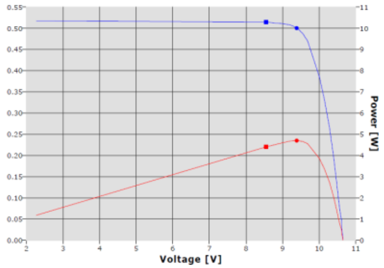
Description	DVT 7
Environment	**GEO** (2100 cycles, -175/+135 °C)
Coupon size	15x40 cm^2
Substrate supplier	Airborne
Lay-out	8 cells in total
N° of strings	1 string
Bare Cell	**3G28C 40x80 mm2, 100µm (JUICE cells)**
Cell Front Interconnector	**Ag three leads (reduced loop)**
Bypass diode	Ext. Silicon diode
By-pass diode front I/C	Ag three leads (reduced loop)
By-pass diode rear I/C	Ag spade
Cell Rear Interconnector	Ag three leads (reduced loop)
Bus Bar	Ag
Rear side elements	None (front side only)

Silver

Task 3: DVTs test

- All DVTs have been submitted to full characterization repeated across their testing lifetime:

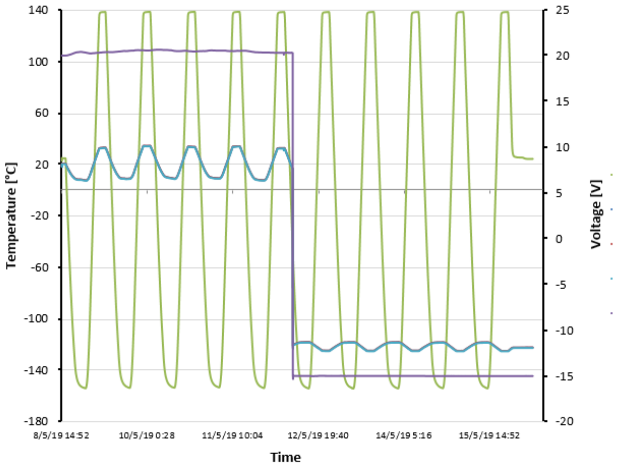
  - Microscope inspection
  - Electroluminescence inspection in visible + IR spectrum
  - Thermography
  - X-rays on interconnects areas
  - Electrical checks (e.g. insulation and continuity)
  - Electrical performance measurements

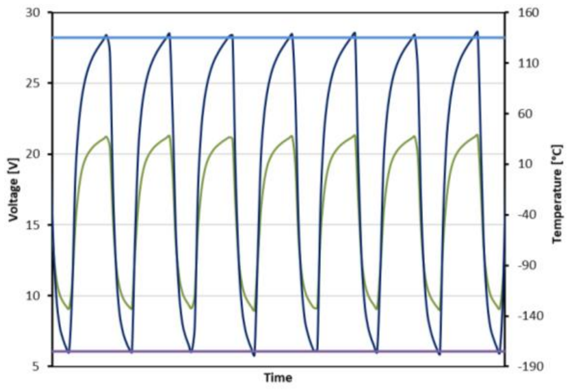


Task 3: DVTs tests

GEO Thermal cycling profile (DVT 3-4-6-7)

Geostationary Orbit Testing Profile
Bake out (24 h at + 95 °C + 24 h at +125 °C)
DVTs inspections and characterizations
10 Thermal Vacuum cycles [-175 / + 135 °C] Electrical continuity monitored
DVTs inspections and characterizations
2100 Thermal shock cycles at ambient pressure [-175°C / + 135 °C] Electrical continuity / insulation monitored
DVTs inspections and characterizations
10 Thermal Vacuum cycles [-175 / + 135 °C] Electrical continuity / insulation monitored
DVTs inspections and characterizations

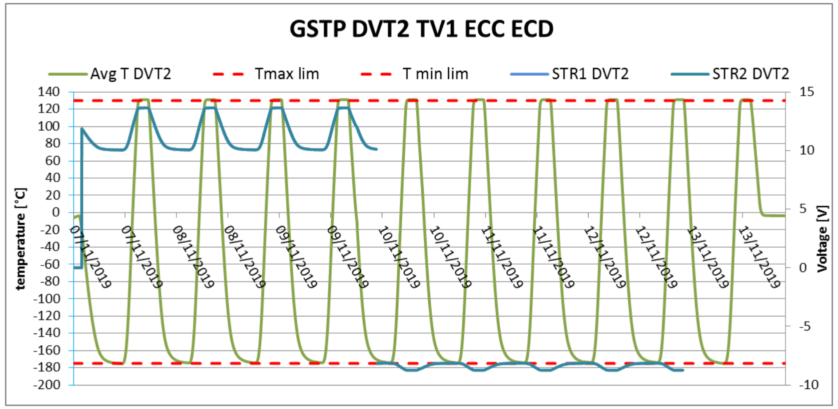


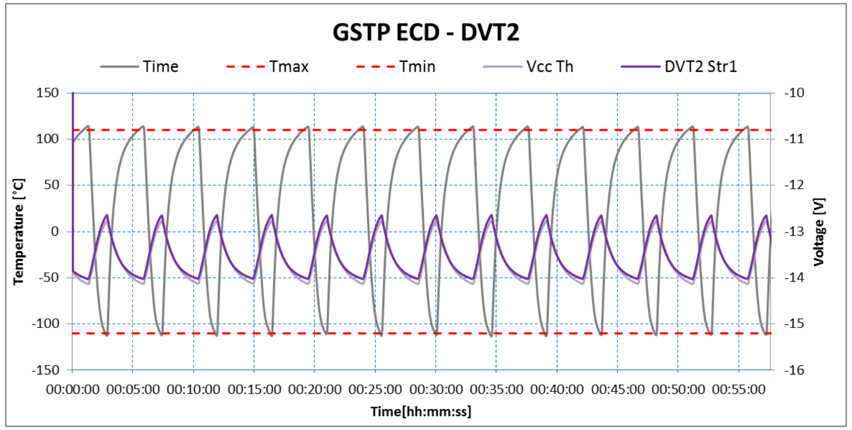


Task 3: DVTs tests

LEO Thermal cycling profile (DVT 1-2-5)

Low Earth orbit Testing Profile
Bake out (24 h at + 95 °C + 24 h at +125 °C)
DVTs inspections and characterizations
10 Thermal Vacuum cycles [-110 / + 110 °C] Electrical continuity/insulation monitored
DVTs inspections and characterizations
100'000 Thermal shock cycles at ambient pressure [-110°C / + 110 °C] Electrical continuity / insulation monitored Interruption for DVT characterization every 20'000 cycles
DVTs inspections and characterizations
10 Thermal Vacuum cycles [-110 / + 110 °C] Electrical continuity / insulation monitored
DVTs inspections and characterizations





DVTs Manufacturing and Test – Conclusions (1/2)

Main conclusions regarding interconnects technology:

- The performed tests confirm that the design of new interconnectors, previously verified by the interconnector FEM analysis and by the associated confidence Flex Test, is suitable for the LEO and GEO environmental conditions. No Interconnector damages have been detected in all the DVTs.

- RODAR:
  - Triple leads Rodar interconnects ensured reliability in temperature excursions (GEO) and extended cycling in LEO: no discontinuities were measured.
  - Bifidus Rodar interconnects have proven to ensure reliability as well, in case of extended cycling in LEO: no discontinuities measured. Bifidus design demonstrated at DVT level the effectiveness of in-plane stress relief.
  - Thanks to the satisfactory weldability of Rodar on cells, no shunts were caused on strings (no power degradation)
  - Visual inspection confirmed the absence of thermal cycling-induced deformations on loops.

DVTs Manufacturing and Test – Conclusions (2/2)

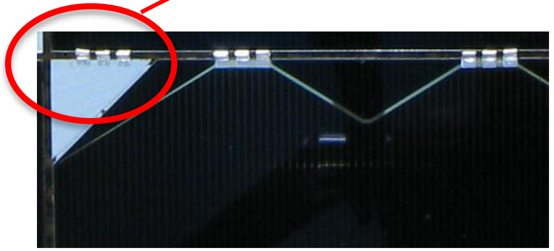
- MOLYBDENUM
  - Triple leads Molybdenum interconnects proved reliability for both LEO and GEO cycling: no discontinuities detected on DVT 2 and 3.
  - Rigidity of Molybdenum prevented the out-of-plane loops to deform during testing phases.
  - It has to be remarked that a not-negligible sensitivity of welding parameters was observed, in response to process variables → to be improved for large production
  - Drawback: cost figure is driven by raw material and sputtering process

- SILVER
  - Triple leads Silver interconnects have been installed on DVT 6 (extended stress relief loop) and DVT 7 (reduced stress relief loop).
  - These two designs proved reliability for GEO cycling, as no discontinuities have been detected during tests and no anomalies were found on EOL visual inspection.
  - On both coupons, no power degradations were measured.
  - Advantage: very good weldability
  - Drawback: material sensitive to mis-handling → reduced loop design used on DVT 7 is preferable

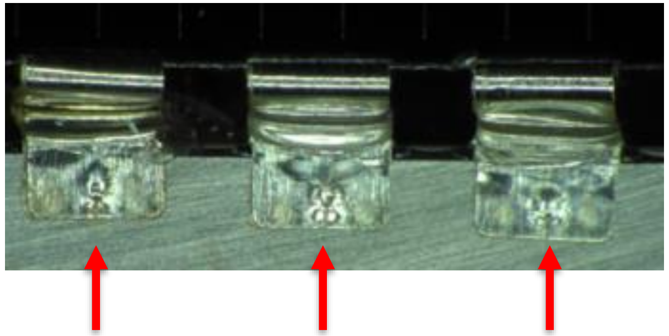
Lessons Learnt (1/2)

Silver weldability on diodes (DVT 6)

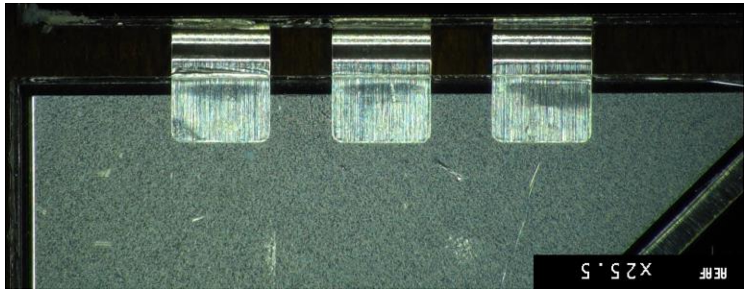
On diodes of DVT 6, interconnects on by-pass diodes occasionally showed welded joints with presence of excess of melted silver



Excess of melted material in correspondence of diodes welded joints



Issue solved on DVT 7 (JUICE technology DVT), manufactured successively (same Ag material), by tuning the welding process



Interconnect welded joints on diodes of DVT 7 (no anomalies)

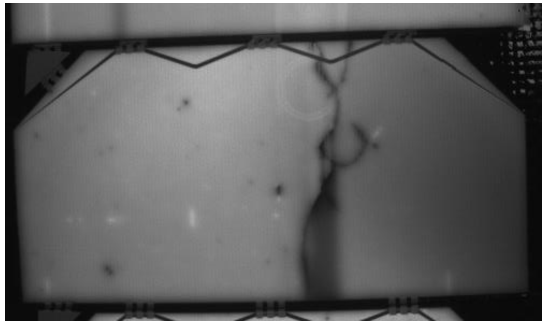
Lessons Learnt (2/2)

Large area Cells bonding

On DVT 4, after APTC cycling (2100 cycles, -175/+135 ° C), a crack was found on 1 cell (3G30, 6x12 cm^2)

The crack did not affect electrical performances of the string and did not evolve after final thermal vacuum test

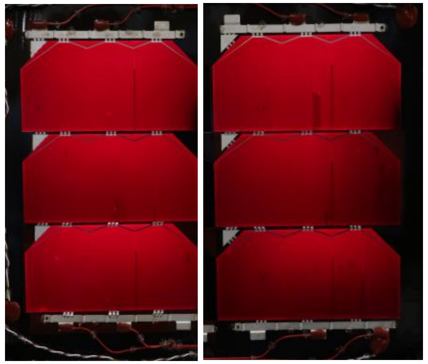
Since no destructive investigations were performed, root cause was not univocally determined, although a dishomogeneity of resin below the cell is suspected



Cracked cell on DVT 4

→ DVT 2 (with Large Area cells as well) was manufactured 3 weeks later with a serigraphic mask more accurately machined than the prototypal one used for DVT 4

→ No cracks were observed on DVT 2 after 100’000 cycles



Nominal cells on DVT 2

Schedule impacts

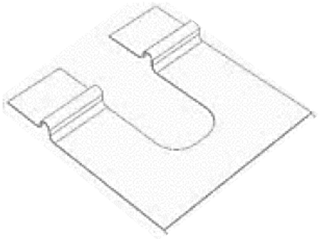
Some occurrences have introduced delays or shifting in the overall program schedule:

- Difficulties in setting up the complete supply chain for Molybdenum Interconnects→ 10 months (+ iterations)
- Difficulties in setting up the complete supply chain for Rodar Interconnects → 6 months
- Introduction of 3 new DVTs proposed by LND (in order to introduce Large Area cells and new configurations)
- Overlapping of ongoing programs (JUICE, etc) workload on resources from R&D and AIT in 2018-2019
- COVID-19 impact → 3 months

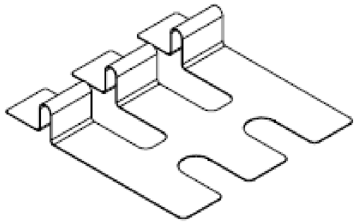
Major outcomes of GSTP 6.1 program (1/4)

- **Development of a new Interconnect baseline technology for Leonardo PVA**

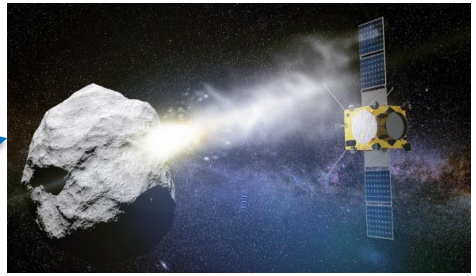
LND Heritage: Ag-plated Invar C-shaped interconnect



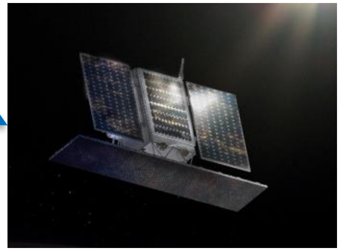
New LND Baseline: Ag-plated Rodar Trident interconnect



Space Rider (ESA)



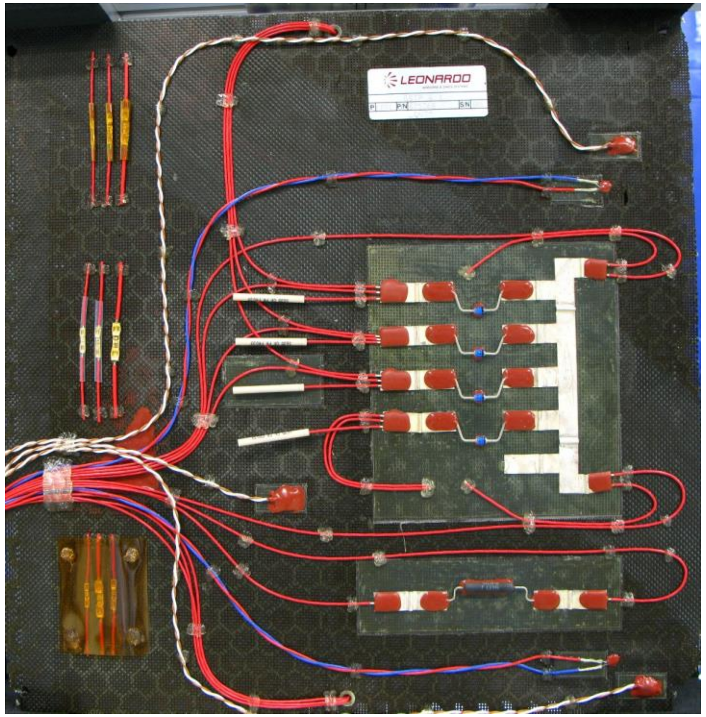
HERA (ESA)



PLATiNO (ASI)

Major outcomes of GSTP 6.1 program (2/4)

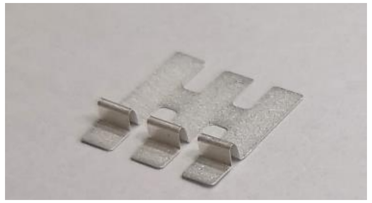
- **Qualification for LEO extended cycling and GEO profile of several rear side components and technologies**



- Diode Boards
- Resistor boards
- Adhesives
- Thermistors M222

Major outcomes of GSTP 6.1 program (3/4)

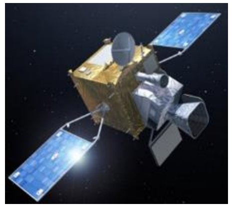
- Updated Leonardo portfolio for interconnect technologies

LEO – GEO missions	GEO missions with magnetic req.	LEO missions with magnetic req.
Silver-plated Rodar	Silver	Silver-sputtered Molybdenum
		
OK	OK	OK although welding sensitivity still to be improved for large productions

Major outcomes of GSTP 6.1 program (4/4)

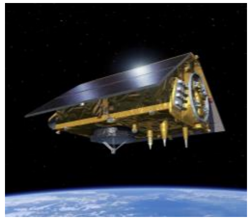
- GSTP 6.1 and the associated environmental testing have furtherly increased Leonardo heritage and PVA capabilities for different missions environments

Extended range - GEO missions



- Meteosat Third Generation
- **GSTP 6.1** (2100 cycles)

Long duration LEO missions



- **GSTP 6.1** (100 k cycles)
- Sentinel 3
- MetOp Second Gen.
- Sentinel 6
- …and others

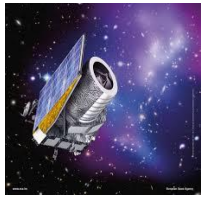
Outer Solar System missions

Rosetta
JUICE
T_{min}= -235 C

Cis-Lunar missions

Orion ESM
T_{min}= -210 C

Lagrangian points missions



- Euclid
- Herschel
- Planck
- Gaia
- …and others

Mars missions

Exomars Missions
- Orbiter
- Carrier
- Rover

Future Developments

- As logical prosecution of the activities carried out in the framework of GSTP 6.1, Leonardo is willing to develop new technologies in the following domains

New SCAs
+ Automation

- Halfpipe layouts
- 4G32
- Low cost / flexible cells

New Interconnects design

- Totally in-plane stress relief loop design
- Electric propulsion compatible materials

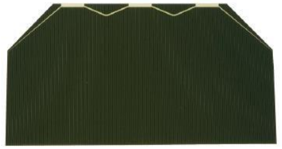
Lightweight PVAs

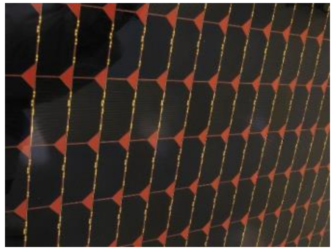
- Highly foldable / flexible substrates
- Rollable substrates

New DVTs (manufactured using automated machines at LND) to be aimed to

- **PVAs for Electric Propulsion platforms**
- **PVAs for Cost-efficient constellations**

Leonardo Technology overview



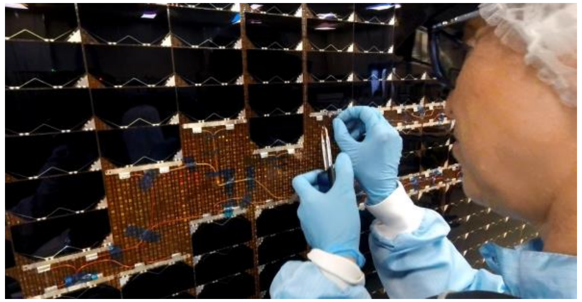


Solar Cells: MultiJunction 30% Efficiency

Joining technology: Parallel gap resistance welding

Bonding: by means of Low Outgassing Space Grade Adhesive

Inspection: Up to 40 times magnification by certified inspectors and automatic system



Electrical Performance Measurement: Sun Simulator, AM0 Spectrum at 1 Solar Constant

Environmental Test Assets: Thermal Vacuum Chamber to simulate Space condition; Ambient Pressure Thermal Shock Chamber for full life Fatigue Test

Manufacturing processes characteristics:

- Fully qualified as per ECSS-E-ST-20-08C
- Suitable for harsh environment in Low Earth Orbit and Geostationary Orbit
- Qualified up to 100'000 Sun-eclipses cycles

JUICE Solar Array (ADSN courtesy)

JUICE panel at Leonardo

CENTRE OF EXCELLENCE FOR PHOTOVOLTAIC ASSEMBLY (PVA)

Automatic processes and production data monitoring

Welding machine for cell joining

Full process traceability

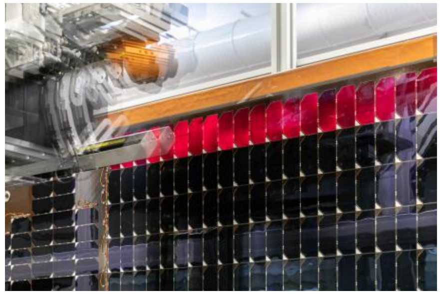
100% incoming check

100% screaning after process

Coverglass bonding

Full process traceability

High process stability leading to reduction of rework after bonding



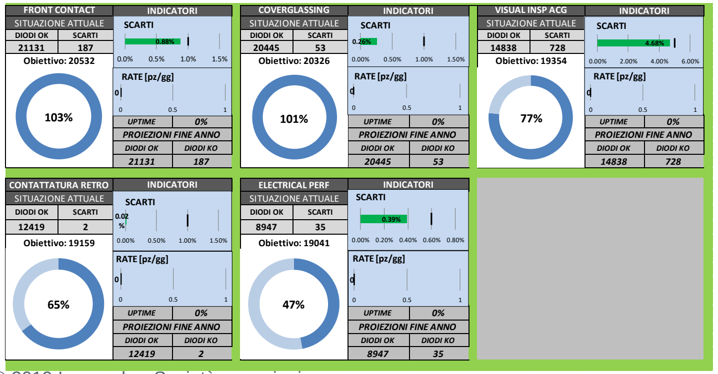
Inspection system:

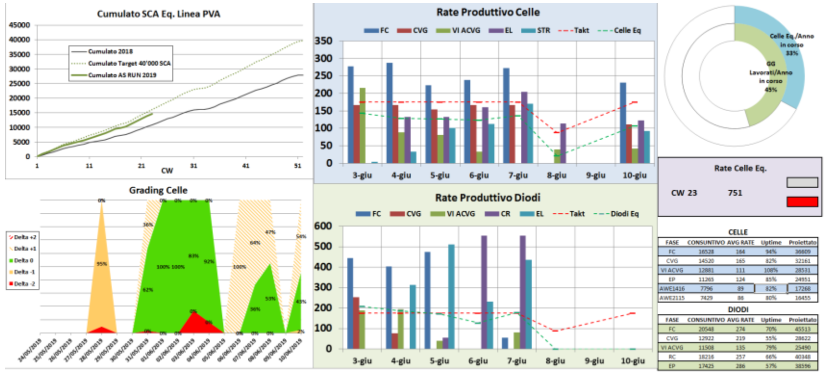
Full process traceability

Electroluminescence Cells Inspection

Thermography for components hot spot identification

Dimensional check





Real time Production Monitoring:

Production rate and yield always under control

THANK **YOU**
FOR YOUR ATTENTION

leonardocompany.com

Questions?