SPARKWING: SMALL SAT SOLAR ARRAYS FROM A CATALOGUE

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PAPER

A new product family of standardized, commercial off-the-shelf solar arrays called Sparkwing has been developed by Airbus Defence and Space Netherlands and qualified for small satellites and LEO constellations in the power range of 100 W to 2 kW. Key drivers for this market segment are minimizing costs, short lead times. Furthermore reducing the stowed stack height while maintaining an overall good performance in terms of stowed and deployed stiffness's are seen as a desirable product feature.

A product catalogue has been set-up, including a variety of panel dimensions with a pre-designed PVA layout (for 36 and 50Vmin). The product concept consists of rigid panels with a central hold-down mechanism and a central spring driven hinge, supported by four force-controlled snubbers.

This approach ensures reduced throughput time and cost by optimization of design, verification and production while still allowing for various configurations. Verification has been done by subjecting the largest catalogue model vibration and acoustic noise testing, followed by a deployment test. Test results were used to calibrate the FEM and to enable verification by analysis of the different catalogue configurations. In addition, two DVT coupons have been tested for 38,000 cycles, one with atomic oxygen protection and one without.

1 INTRODUCTION

The market segment of small satellites has been growing steadily over the last few years with many new and established players entering the segment with their products and satellite platforms. Airbus Defence and Space Netherlands entered this segment by developing a dedicated product line called Sparkwing. Sparkwing is a product line which focusses on satellites with a power need between 100W and 2kW and deployable wing with panel sizes <1.5x1.5m and maximum number of panels of 3 per wing.

This paper introduces the specific requirements of the small satellite industry for solar arrays, the decision behind the Sparkwing catalogue approach and the overall product concept and the dedicated building block necessary. Subsequently the paper touches on the development, testing and correlation activities performed over the course of the design and validation phase and finishes with a brief discussion about the industrialization approach.

2 REQUIREMENTS

The market needs or requirements set by the small satellite primes on the solar array product vary from mission to mission as earth observation and last-mile transportation platforms have different needs. Airbus Defence and Space Netherlands however did manage to distill a set of requirements that allowed the design of the Sparkwing product to be compatible with 80% of the missions.

Capturing the remainder of the missions would have led to overdesign of the product and these mission can still be served with customization effort.

The main requirements identified are:

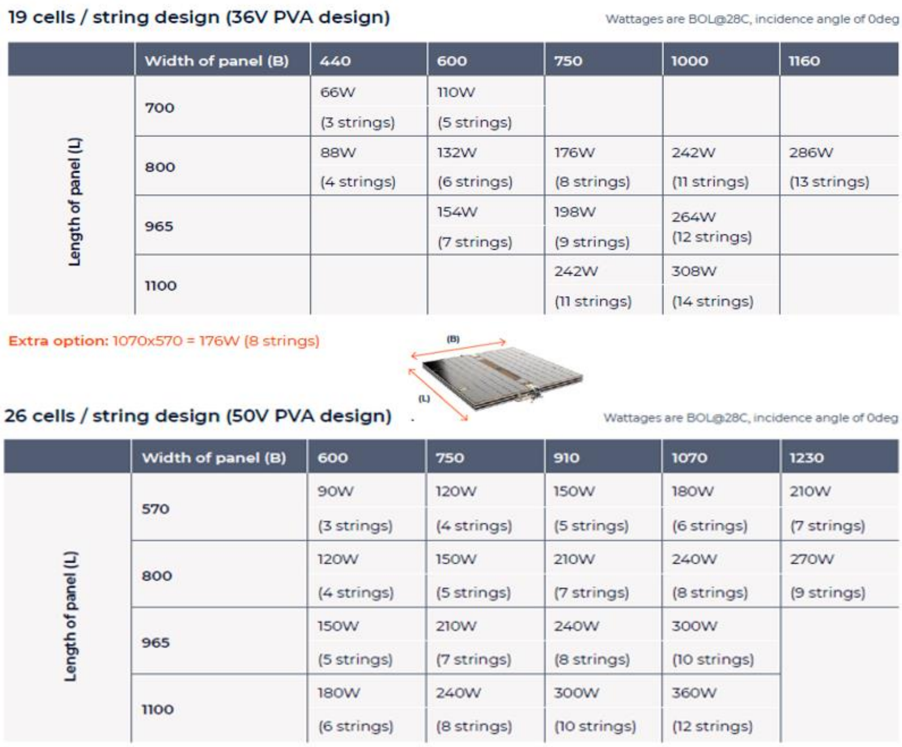
- Low cost: prices of platforms are going down driven by technological advances but also the need to be competitive with the end product (the overarching business case).
- Short lead times: time-to-market is vital for many new services, also the increased launch opportunities and appetite to experiment drive the need for shorter lead times in the industry.
- Power range 100W to 2kW: a range that allows serving the lower end of the small satellite market up to the high end of the market as seen today.
- Low build height: rideshare slots are generally volume constraint instead off mass constraint, as the solar array build height will directly impact the internal satellite volume there is a need to keep the solar array build height as small as possible.
- Deployed frequency: mostly driven by the stability of the earth observation payloads, the deployed natural frequency is to be optimized (taking into account other limitations)
- Orbits: a majority of the small satellite missions still situates itself in LEO, therefore any solution should be optimized for this orbit however operation in MEO, GEO should be feasible with minor adaptations
- Connection to SADA: most small satellites do not operate a SADA to steer the solar array, however some missions do so the concept should allow for connecting the solar array to a SADA
- Easy integration: week long integration activities of the supplier at the prime are inefficient and for these small products also unnecessary, meaning easy integration is expected.

3 CATALOGUE APPROACH

When considering the typical power ranges, voltage preferences, platforms sizes and launch envelopes, it was concluded that the remaining design space was such that it could be served with a catalogue of standard solar arrays that are flexible in their configuration. This approach allowed the team to define a solar array based on one common design that fits 80% of the smallsat missions in the Sparkwing power range based on a set of standard panel sizes and a single common qualification. Furthermore the design is flexible enough to come to a tailored design for a large portion of the remaining 20% at limited additional effort.

Compared to fully customized designs, like it is common in the industry, it has the advantage that the Sparkwing configurations are designed and verified already, greatly reducing the design phase and performance uncertainty.

The catalogue addresses the two main bus voltages, namely 36V and 50V busses, by providing standard lay-outs with 19 3G30A cells in series and 26 3G30A cells in series. The 3G30A solar cell is the state-of-the-art 30% efficient solar cell by AzurSpace. The various dimension, see Figure 1, are determined by looking at different rideshare volumes, ideal PVA lay-outs and various customer requests. The amount of panels per wing the concept can support is 1 to 3 panels.



19 cells / string design (36V PVA design)

Wattages are BOL@28C, incidence angle of 0deg

	Width of panel (B)	440	600	750	1000	1160
Length of panel (L)	700	66W (3 strings)	110W (5 strings)			
	800	88W (4 strings)	132W (6 strings)	176W (8 strings)	242W (11 strings)	286W (13 strings)
	965		154W (7 strings)	198W (9 strings)	264W (12 strings)	
	1100			242W (11 strings)	308W (14 strings)	

Extra option: 1070x570 = 176W (8 strings)

26 cells / string design (50V PVA design)

Wattages are BOL@28C, incidence angle of 0deg

	Width of panel (B)	600	750	910	1070	1230
Length of panel (L)	570	90W (3 strings)	120W (4 strings)	150W (5 strings)	180W (6 strings)	210W (7 strings)
	800	120W (4 strings)	150W (5 strings)	210W (7 strings)	240W (8 strings)	270W (9 strings)
	965	150W (5 strings)	210W (7 strings)	240W (8 strings)	300W (10 strings)	
	1100	180W (6 strings)	240W (8 strings)	300W (10 strings)	360W (12 strings)	

Figure 1: Sparkwing catalogue, various panel sizes

4 DESIGN CONCEPT and BUILDING BLOCKS

The challenging requirements, especially short lead time and ease of integration drive the design concept, which can be seen in Figure 2.

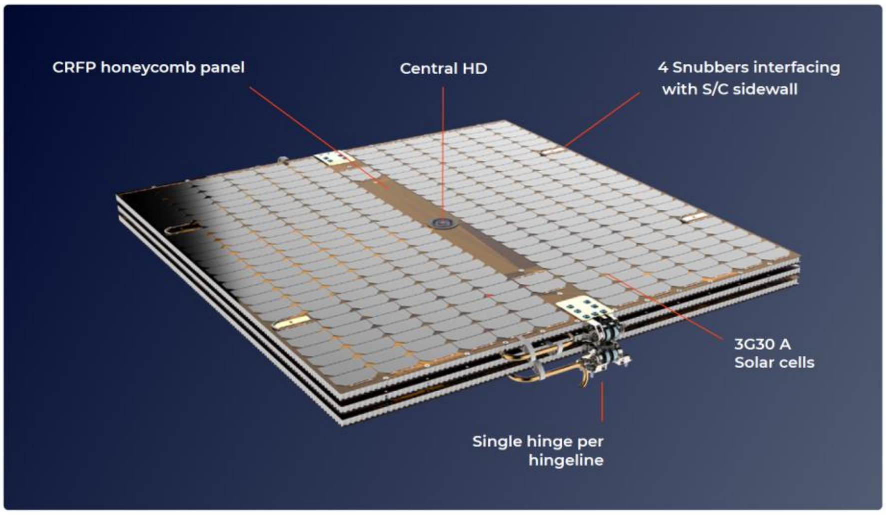


Figure 2: Sparkwing design concept

The main design features are:

- The use of one central hold-down and release mechanism instead of multiple mechanisms placed across the panel. This reduces the actuation needs from the satellite, hard (bolted) connections to the satellite and reduces risks (less mechanisms). It however also has positive implications for the solar array as it allows for easier integration since there are no tight tolerances to ensure between different hold-down locations.

- A single spring-driven hinge per hingeline instead of multiple. This choice was made to limit the amount of mechanisms and as such complexity, risk and integration time. The additional advantage of a single hinge per hingeline is that there is no additional design effort required to implement a SADA connection. The Roothinge is the second hard (bolted) connection with the satellite.
- Four force-controlled snubbers that are only resting on the sidewall of the satellite, so a soft (non-bolted) connection, to ensure adequate stowed dynamic performance. The location of the snubbers can be moved across the panel in order to tweak the stowed Eigen frequency or to avoid certain equipment located on the sidewall of the satellite.
- No damping or synchronization elements, this is reducing complexity, cost and mass of the system. As this design choice might not be straightforward, many deployment analyses have been performed in MSC ADAMS (multi-body software) to ensure that even in extreme cases the deployment behavior is acceptable.

The main building blocks are (also see next subsections):

- Thin (15mm) sandwich panels supporting the PVA.
- PVA based on the Azur 3G30A cell
- Hold-down and release mechanism
- Spring-driven hinges
- Force-controlled snubbers
- Transfer harness

4.1 Building block: Sandwich panels

The sandwich panels are uniform panels consisting of CFRP facesheets with an aluminium honeycomb. The sandwich panels are kept thin (15mm) in order to reduce the stack height in stowed configuration to a maximum extend while also ensuring a good performance in terms of stiffness (1st Eigen frequency) in deployed configuration. Figure 3 shows the panel component.

Figure 3: Sparkwing sandwich panels

To shield the CFRP facesheets electrically from the cells a layer of kapton is added to the top side of the panel. Additionally a layer of atomic oxygen protection can be applied to ensure lower orbits can be flown with the product.

To allow the mechanism to be attached to the panel bracketry are glued to the uniform substrate afterwards.

4.2 Building block: PVA

The PVA design’s main component are the Azur 3G30A cells, these are high (W/m^2) performance cells used widely across the industry. These cells are connected together and protected by integral shunt diodes between the cells as well as one blocking diode per sting. Exact stringing and sectioning depends on the catalogue configuration chosen, standard ESD and magnetism provisions are taken into account. Additionally the wing is protected by a grounding circuit and a bleed resistor towards the satellite.

4.3 Building block: Hold-down and release mechanism

The central hold-down and release mechanism uses a commercially available actuator from Glenair. This reduces developed time but also ensures that a frequently used and well characterized mechanism is used reducing risks and cost (as it is produced in greater numbers). Adding to the COTS actuator is an in-house developed housing, see Figure 4 and bolt retraction mechanism, the latter to ensure that the released bolt does not hit any of the panels whilst the panels are moving outwards.

Figure 4: Central hold-down and release mechanism

The hold-down and release mechanism is developed such that it does not require a lot of space below the panel stack, this ensures that the requirement of a low total stack height can be achieved.

4.4 Building block: Spring driven hinges

The spring driven hinges are derived from the legacy single hinge per hingeline designs available within Airbus Defence and Space Netherlands (e.g. as used for the Galileo program) to ensure they rely on all the lessons learned over the year. The challenge however lies in the greatly reduced available volume of the Sparkwing product as well as the need to retain a certain stiffness as well as reduce complexity and cost.

These challenges lead to a design for the inter-panel hinges and Roothinge that is shown in Figure 5. The design is spring driven, meaning it is a passive system and actuation will start after release of the hold-down and release system. The design features double arms to ensure that also in-plane and torsional stiffness is ensured. The Roothinge design has 4 bolts towards the spacecraft and the location is placed such that they can always be accessed in stowed condition (easy integration).

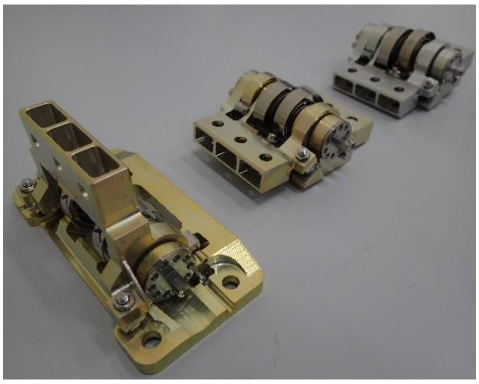


Figure 5: Roothinge (left) and inter-panel hinges (middle and right)

4.5 Building block: Force controlled snubber

The four force controlled snubber stacks transfer the out of plane loads to the sidewall in the stowed configuration. A force control mechanism was introduced to ensure that a pre-calibrated preload is introduced in the snubber stack just by a torque wrench. The preload does not depend on the snubber height, so there is no need for shimming or high flatness requirements on the spacecraft sidewall. The required preload is adjustable and is determined from finite element analysis. It is ensured that no gapping occurs between the panels in the stack.

4.6 Building block: Transfer harness

The transfer harness consist mainly of AWG22 space approved wiring bundled together and applying the standard de-rating rules. The harness is lead across the panels in a torsion bundle to limit the retarding torque of the harness during deployment. Together with limiting the number of cables by putting a maximum number of sections in place this allows the design to remain without damper and synchronization units.

The connection to the satellite is made with a 37 pins sub-D connector with pre-set pinout, although alternative connectors can be easily accommodated if required.

5 DEVELOPMENT

The development approach has been two-fold, first a highly iterative design phase was put in place to ensure multiple designs, technologies and different sets of customer requirements could be evaluated at a high pace. After converging to one design concepts and set of customer requirements the development followed the well-known V-model for development and verification activities.

Central in the design decisions are the design to cost element and design for catalogue optimization, as optimizing for one configuration could lead to issues with other configurations. During development the team used many component breadboards and engineering models to find and eliminate potential issues later on. The breadboards and engineering models were also used to get early feedback from suppliers and the AIT department as simple changes did lead to major cost reductions.

The development approach is shown in Figure 6.

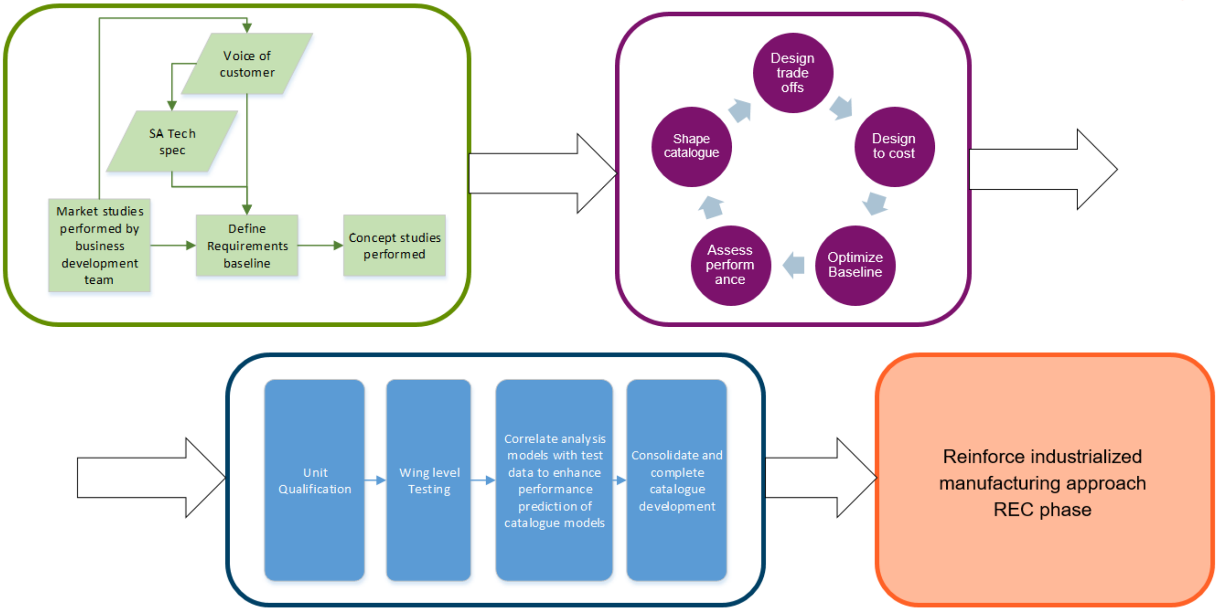


Figure 6: Sparkwing development approach

After the design the full set of unit qualification testing normally expected for space products has been performed followed by producing and testing one wing model. The exact configuration chosen is the largest catalogue configuration with the most unfavorable snubber positions. This configuration is chosen as it is critical in terms of mechanical loading of the subsystems (same levels applied as would be applied for smaller models) and also results in the most critical interface loads.

After unit testing and wing level testing all the information is used to correlate the FE model. Using the test data and the correlated model gives very high confidence in the other configurations as loads are lower and frequencies can be predicted with high accuracy.

A last step that has been taken as part of the development is design of an industrialized approach for recurring production of the product. This industrialization effort took into account that many different configurations have to be made on the same production line.

6 VERIFICATION and CORRELATION

6.1 Unit testing

Unit testing has been performed on all subsystems to characterize and validate the designs. Not all testing performed will be highlighted in this paper, however some major components and tests are shown.

A first critical aspect already highlighted earlier is the retarding torque of a hingeline as it determines the motorization energy that has to be put into the system and subsequently the latch-up loads at the end of deployment. Second, it is also important that this retarding torque can be applied consistently and has little variation between build (although it is measured for every FM as an acceptance test).

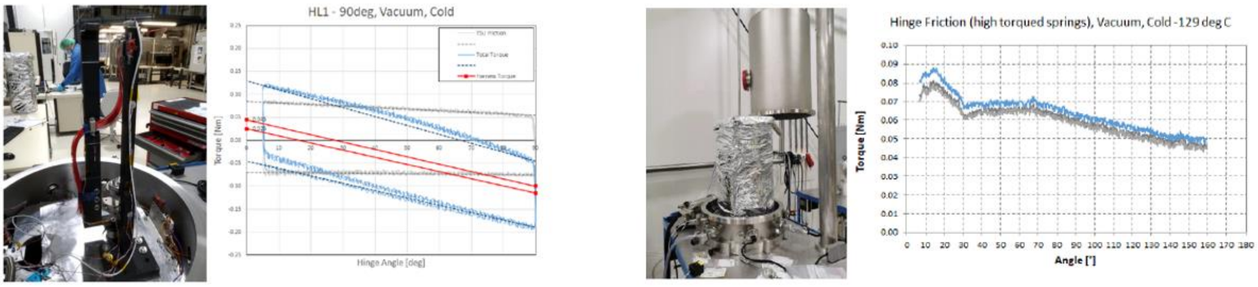


Figure 7: Harness retarding torque test (left); Hinge friction test in vacuum (right)

To verify the total retarding torque is within the set limits both harness retarding torque and hinge friction (see Figure 7) is tested separately in various condition. These conditions are ambient and vacuum as well as at various temperatures. Retarding torque and friction are measured over the complete opening angle of the hinge to allow full characterization. For the hinge also stiffness and strength testing will be performed under the same conditions.

A second subsystem to highlight is the hold-down and release mechanism. This component is vital for the solar array as its functioning determines if the solar array will deploy. Functional testing in space representative conditions is therefore a must, both on the COTS actuator as on the in-house developed additional elements. Next to functional testing the hold-down and release mechanism is placed in a bigger subsystem (stack of 3 panels, see Figure 8) and tested to launch vibration levels. Both sine and random vibration qualification levels are put on the assembly after which a hot release (release of the actuator) is performed to show the system is not damaged during vibration.

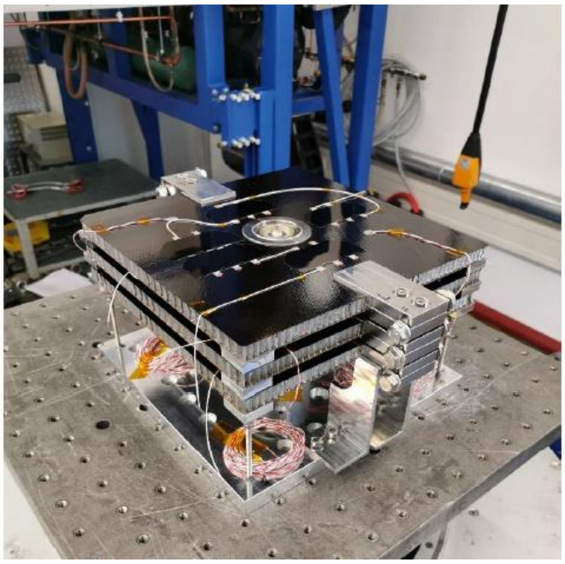


Figure 8: Vibration testing of hold-down and release mechanism stack

Another key test performed is substrate testing (see Figure 9), the materials used are used in other product before however the lay-up and core height differ so the stiffness and strength test allowed to identify variations and determine A and B values for these parameters.

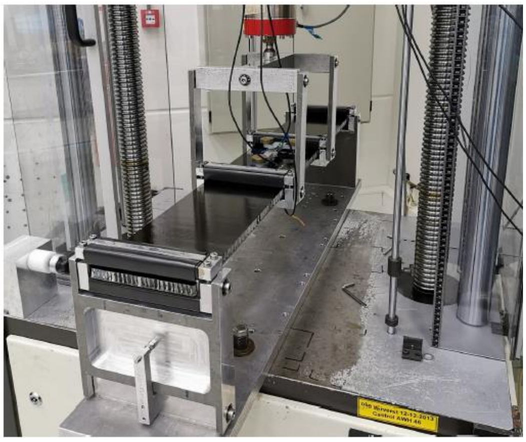


Figure 9: 4-point bending substrate testing

The last unit test to highlight is testing of the PVA. The separate components are well-know and used in many space programs, so fundamental EEE testing was not necessary in the frame of this product development. Testing focused mainly on production process testing and testing two DVT units to validate the PVA and substrate combination under prolonged thermal cycling. One DVT unit has atomic oxygen protection applied whereas the second unit has not. Both units will be tested for LEO temperature environment (+/-110ºC) and 5 year lifetime (38k cycles). At regular intervals an electro luminescence measurement (ELM) test will be done to check for damage, see Figure 10.

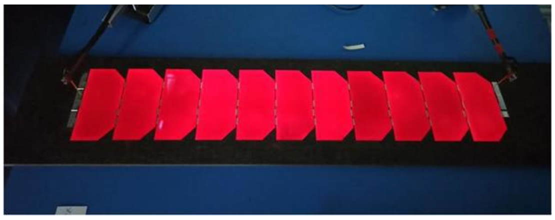


Figure 10: DVT ELM test, source: DHV technology

6.2 Wing level testing

As part of the development one catalogue configuration has been tested to qualification levels. As mention in an earlier section the configuration chosen is the largest catalogue configuration with the most unfavorable snubber positions. This configuration is chosen as it is critical in terms of mechanical loading of the subsystems (same levels applied as would be applied for smaller models) and also results in the most critical interface loads.

The main tests performed on the full wing are:

- Visual checks throughout the assembly, integration and testing flow
- Electrical health checks and performance measurement pre and post vibration testing
- Sine (including QS levels in the low frequency range), see Figure 11
- Random vibration testing, see Figure 11
- Acoustic noise testing
- Deployment testing pre and post vibration testing, see Figure 12
- Stiffness and alignment performance pre and post vibration testing, see Figure 13

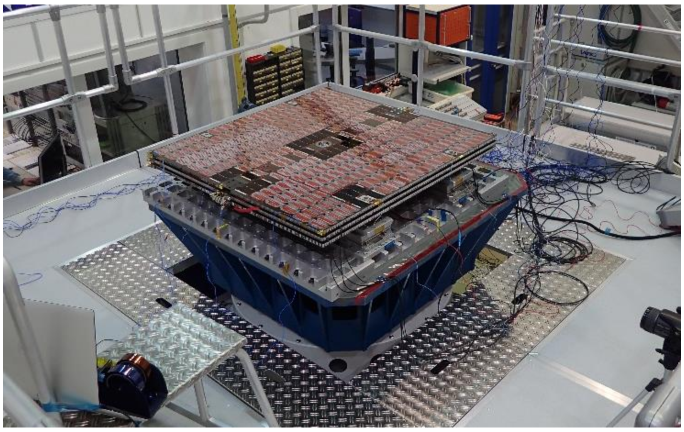


Figure 11: Full wing testing on the IABG shaker

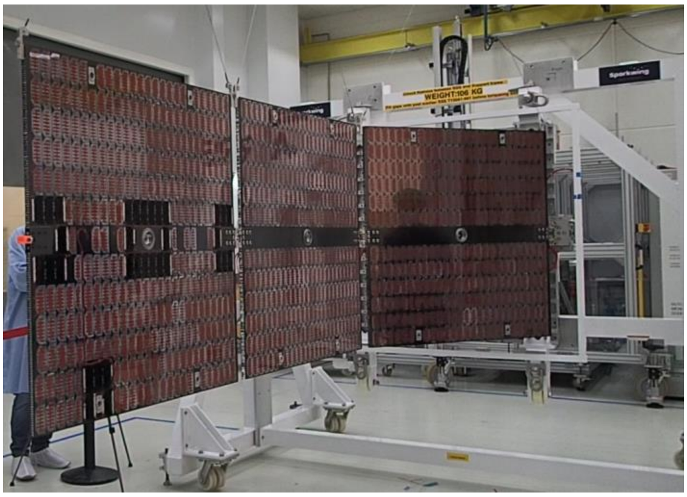


Figure 12: Deployment testing at the Airbus Defence and Space Netherlands facilities

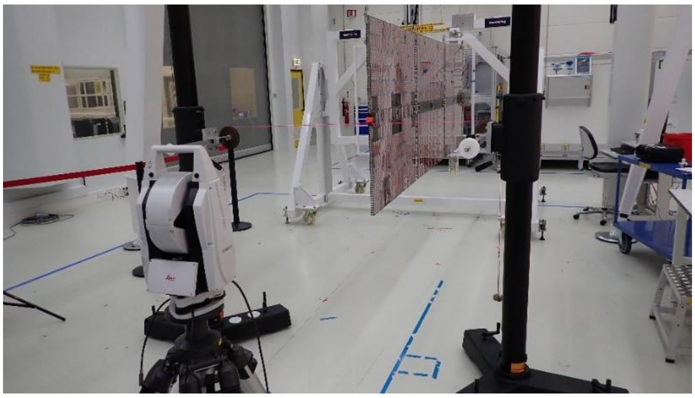


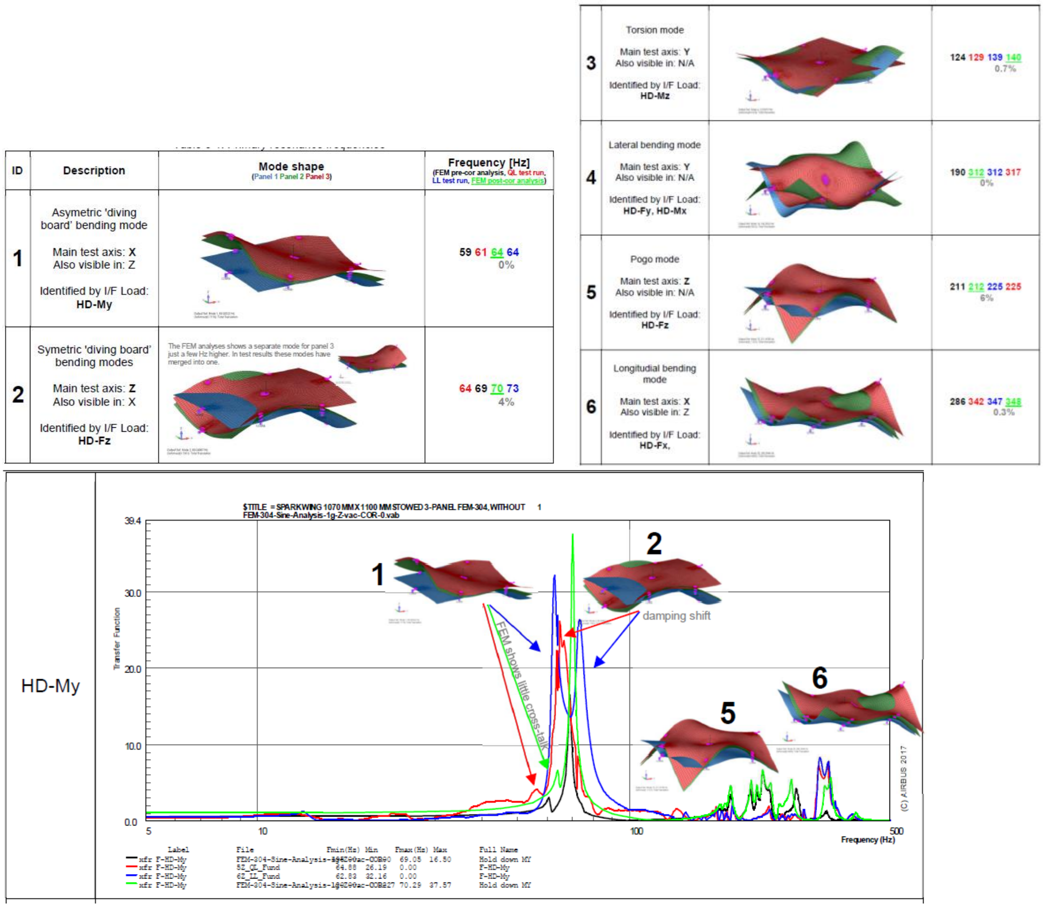
Figure 13: Laser tracker assisted stiffness and alignment performance testing

6.3 Model correlation

As mentioned in the previous section the most critical (mechanically) catalogue model has been put through an extensive test program proving that the Sparkwing building blocks and end product are capable of reaching the levels set as requirement for the product line. As the other configuration are less critical (read: will have higher margins of safety all around) there is no need to test every single model. It is however important that the FE models and as such the data and models customers receive for their specific configuration has a high accuracy.

To obtain a FE model with high accuracy all the data from the unit and full wing level testing has been used to correlate the model, the unit test data allowed to tune the right parameters (read: have a physical meaning) rather than using a relatively random parameter to tune.

The result (see Figure 1) shows that the FE model pre-testing was already very accurate, mainly due to the extensive breadboard and unit characterization testing. Further slight tweaks ensure that the model has 4 out of the first 6 modes within 1% of the actual frequency, furthermore the remaining two modes are around 5% deviating which is considered highly accurate for any model.



ID	Description	Mode shape (Panel 1 Panel 2 Panel 3)	Frequency [Hz] (FEM pre-cor analysis, QL test run, LL test run, FEM post-cor analysis)
1	Asymetric 'diving board' bending mode Main test axis: **X** Also visible in: Z Identified by I/F Load: **HD-My**		59 61 64 64 0%
2	Symetric 'diving board' bending modes Main test axis: **Z** Also visible in: X Identified by I/F Load: **HD-Fz**	The FEM analyses shows a separate mode for panel 3 just a few Hz higher. In test results these modes have merged into one.	64 69 70 73 4%
3	Torsion mode Main test axis: **Y** Also visible in: N/A Identified by I/F Load: **HD-Mz**		124 129 139 140 0.7%
4	Lateral bending mode Main test axis: **Y** Also visible in: N/A Identified by I/F Load: **HD-Fy, HD-Mx**		190 312 312 317 0%
5	Pogo mode Main test axis: **Z** Also visible in: N/A Identified by I/F Load: **HD-Fz**		211 212 225 225 6%
6	Longitudial bending mode Main test axis: **X** Also visible in: Z Identified by I/F Load: **HD-Fx,**		286 342 347 348 0.3%

Figure 14: Commercial engineering model FEM correlation

To be able to deliver FE models quickly to customers while configuration and especially snubber configuration can change, the above correlated model and the catalogue configuration is used to set-up an automatic FE model generator. This model also has some checks build inside so that the mechanical engineer has all the information needed to asses that the generated model is indeed correctly constructed.

7 INDUSTRIALIZATION

The requirements showed that cost and lead-time are two main considerations for small satellite customers for which the Sparkwing product has been developed. Design is certainly a big part of making this happen however also the industrialization part is as important to obtain the goal of reducing those parameters.

As part of the industrialization effort two different axes are explored, namely creation of a production line and workstations (see Figure 15) to optimize throughput for small constellations (5-10 satellites per year) for multiple customers per year taking into account that these multiple customers can have different configurations. Also taken into consideration is future upscaling of production to ensure the Sparkwing product can be delivered when demand increases.

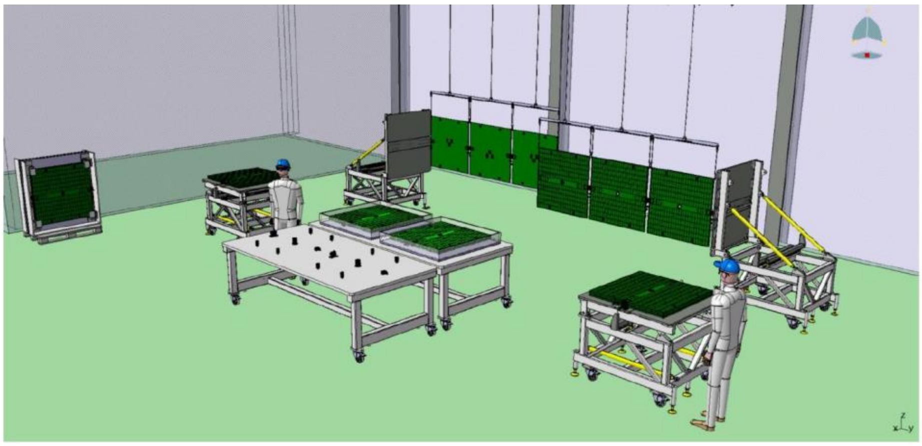


Figure 15: Production line for the Sparkwing product

Secondly the Sparkwing team looked at the acceptance test flow and took into account the extensive test program, multiple similar tests at different stages and extensive heritage with not only Sparkwing but also other solar array products to eliminate some of the tests in the process while not cutting back on quality.

One example to mention is TVAC testing, which is a costly endeavor, this test will be performed on the first 10 panels and afterwards be phased out. This can be done using the extensive experience with solar arrays and when cells cracks emerge combined with the statistical data from these first 10 panels and the tight production processes and control of those. Note that a bake-out is still done on all panels.

Also part of the industrialization effort is design of the transport container and placement of the wing onto the satellite by the customer. The Sparkwing product can be transported in stowed configuration and does not require a separate deployment test at the customers premises, reducing integration time and as such cost. As shown in previous sections the solar array design is optimized for this, however also the GSE has gone through an extensive design cycle to make this achieve this.

8 CONCLUSION

The main challenge of designing a new solar array product especially tweaked to the requirements of the small satellite market by Airbus Defence and Space Netherlands has been shown in this paper. It addressed the different design choices made, especially the central hold-down reduces tolerance issues and enables easy assembly and integration. The paper also showed the building blocks necessary and the steps taken to develop and test these units successfully. It also shows the testing performed a full wing, the most critical configuration of the catalogue to prove the products capabilities as well as enabling correlating the FE models for the complete catalogue. Lastly the industrialization aspect is addressed as it is important to think about the production line that enables different configurations to be built on the same line.

The next steps for the Sparkwing product, now that the development and verification is successfully completed is delivering he product to the first customers (in progress at time of writing). The team is next to delivering also already looking at future improvement to enable more challenging missions, but also to improve on cost, lead time and performance.