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DEVELOPMENT OF A NEW, HIGH-POWER SOLAR ARRAY FOR TELECOMMUNICATION SATELLITES

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ABSTRACT

Airbus is currently developing the Next Generation Solar Array (NGSA) for telecommunication satellites. It is based on a hybrid array concept which combines a conventional rigid panel array with lightweight, semi-rigid lateral panels. The main figures of merit power/mass and power/volume can be doubled through this concept. Mechanically, the semi-rigid panels are the key new element. Through acoustic testing as well as sine vibration testing in air and in vacuum it was verified that these panels are suitable as cell support in stowed configuration. With the help of finite element modelling it is demonstrated that the semi-rigid panels are compatible with a free deployment. Electrically, the new array is to be equipped with a new generation of 4 junction solar cells with efficiencies above 30%. The increased radiation dose due to electric orbit raising has to be taken into account to arrive at the optimum shielding while still minimizing the array mass. By adjusting the ratio of rigid to semi-rigid panels and through the choice of solar cell type and mass, the NGSA can be tailored in a wide range to needs of a given platform. This is illustrated for the solar array to be flown on the new Airbus platform Eurostar Neo.

1. INTRODUCTION

Airbus is currently developing the new telecommunication platform Eurostar Neo, which is optimized to an even higher degree than its predecessor Eurostar 3000 for the payload. This payload centric design imposes new, much more stringent requirements onto the solar array. Most notably, the stowage volume available to the solar array on the satellite sidewall is reduced, both in terms of surface area as well as in stack height. At the same time, the power demand has increased by 50%, compared to previous Eurostar solar arrays. Due to the focus on electric orbit raising, the radiation fluences are also increased up to five times.

To address these challenges, we rely on the concept of a hybrid solar array, which was already suggested several years ago[1]. There, a backbone, resembling a conventional rigid panel array is combined with lightweight, semi-rigid lateral panels. During launch, these panels are folded in between the rigid panels and are thus protected. This Next Generation Solar Array (NGSA) is developed in the frame of the ESA ARTES funding lines.

OVERALL SOLAR ARRAY DESIGN – THE HYBRID CONCEPT

These key features of the NGSA are illustrated in Fig. 1 in deployed and in Fig. 2 in stowed configuration.

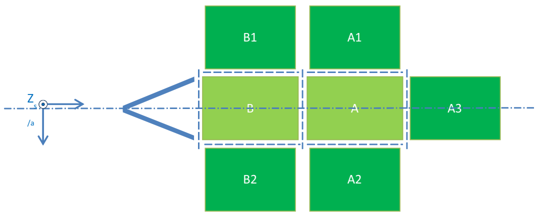

Figure 1: Schematic illustration of the solar array concept. Conventional rigid panels are indicated in light green and the new semi-rigid lateral panels are dark green.

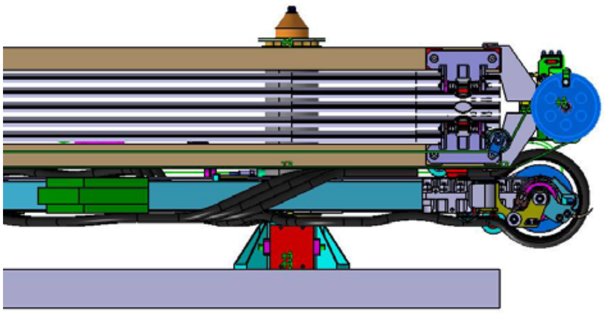

Figure 2: Cross sectional view through the solar array stack in stowed configuration.

In Fig. 2 the most important advantage of the hybrid array concept is directly evident, the semi rigid panels are much thinner than the conventional honeycomb panels and in addition can be stacked much closer than in conventional arrays. Therefore the stowage volume is greatly improved. In addition, their aerial mass is 5 times lower compared to the rigid panel and combined with the use of lightweight cells, the power to mass ratio of the array is also improved significantly. Based on the maximum configuration with 5 semi-rigid panels sandwiched between two rigid panels, illustrated in Figs. 1 and 2, a whole array family can be constructed based on the needs of a given platform.

In Table 1, the performance figures of the NGSA concept are summarized for a 2 rigid / 5 semi-rigid panel version consisting of Eurostar 3000 panel sizes, which equate to a surface area of 9 m² per panel. Eurostar 3000 is Airbus's current solar array for telecommunication missions, consisting of a conventional rigid in-line panel configuration. As reference, the performance of the largest version, consisting of 5 rigid panels, is included as well. In terms of radiation dose, a classical 15 year GEO mission with purely chemical transfer orbit is assumed and the end-of-life (EOL) summer solstice (SS) power figures are computed. Both mass and stowage volume figures are "real" figures in the sense that they include yoke, yoke hinge as well as all hinges and hold-down and release units. The stack height is calculated from the satellite sidewall up to the outermost panel.

Table 1: Main performance figures of the NGSA in a standard GEO mission scenario.

version	E3000 5L	NGSA 2+5	NGSA 2+5	NGSA 2+5
cell type	3J 30%	3J 30%	3J 30%	4J 33%
cell thickness [µm]	140	140	20	20
coverglass [µm]	100	100	50	50
mass [kg]	302	284	205	205
power EOL SS [kW]	19.8	26.9	26.5	29.5
power/mass [W/kg]	65	95	129	146
power/ volume [kW/m3]	4.2	7.2	7.2	8.0

According to Table 1, the NGSA concept is capable of approximately doubling the main figures of merit, power/mass and power/volume, compared to the conventional rigid panel arrays in use today. Table 1 also highlights the main contributing factors. The hybrid array concept by itself improves power/mass by 44% and the stowage volume by 72%, as evident from the third column in Table 1. The reduction in solar cell assembly (SCA) mass from a classical 140 µm cell/100 µm coverglass configuration of 3.5 g for a 30 cm^2 SCA to a lightweight 20 µm cell and 50 µm coverglass configuration of 1 g in column 4 improves power/mass by an additional 37%. Finally using a lightweight 4J cell with a 10% increased EOL efficiency of 29% at 10^{15} 1 MeV e- /cm^2 results in an identical 10% increase in power/mass and power/volume again, as shown in column 5.

2. CONCEPT VERIFICATION

This increase in power/mass and power/volume by a factor of two is especially attractive due to the fact that it is achieved by a solar array design that relies in large parts on components with extensive space heritage. What has to be ensured, however, is that the solar cells on the semi-rigid panels can actually survive the mechanical loads occurring during launch. Although the hybrid solar array concept has been suggested several years ago, the actual feasibility of the concept has not been experimentally verified up to now.

Figure 3: Semi-rigid panel equipped with solar cells and SCA mass simulators.

For the experimental verification, two semi-rigid panels, 3.9x 2.3 m in size were built and equipped with 30% efficient triple junction cells in representative areas, as illustrated in Fig. 3. The cell thickness varied from 20 – 80 µm and 50 µm and 100 µm coverglasses were used in order to cover a range of SCA masses. The two semi-rigid panels were sandwiched between two rigid panels, and the entire stack was subjected to three axes sine vibration testing, with 4 g input out-of-plane, notched for the first resonance frequency of the rigid panels, and 6 g for the two in-plane tests.

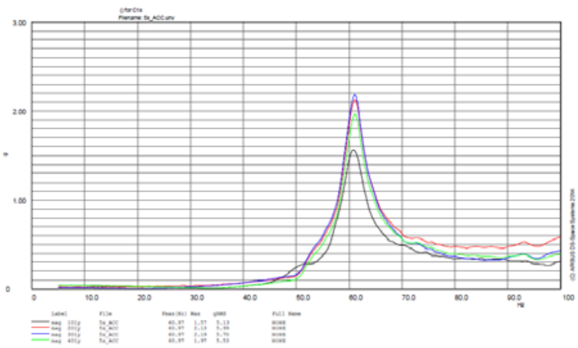

Figure 4: Accelerations measured during the in-plane sine vibration testing on the 2 rigid and 2 semi-rigid panels at identical position.

All sine vibration tests were carried out successfully. The cell integrity was not affected. Both rigid as well as semi-rigid panels were equipped with accelerometers during test. In Fig. 4 the accelerations measured on 4 sensors located at the same position on each panel during the in plane test are shown as an example. All accelerometers show the same resonance frequency around 60 Hz. In particular no resonance frequency of the semi-rigid panels, expected in the lower frequency range is observed. A more detailed analysis confirmed that the enclosed air in the stack resulted in significant damping as well as an in-phase movement of the semi-

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rigid panels with the rigid panels.

In addition, standard acoustic noise testing was carried out on the same stack with a maximum sound pressure level of 145 dB for 70 s and with 155 dB for 10 s. Again the test was completed successfully, with no cracked solar cells as well as no damage to the rigid or semi-rigid substrates observed.

These sine vibration and acoustic tests confirmed the basic feasibility of the hybrid solar array concept. They however also highlighted the important effect air damping has on the stack. Since during an actual launch the evacuation of the fairing proceeds much faster than the acceleration loads are reduced, two important conclusions result: i) for the semi-rigid panels it is not possible to rely on the effect of air damping and ii) the stacked configuration has to be subjected to a sine vibration test under vacuum.

3. SEMI-RIGID PANELS

The central element of the NGSA concept are the semi-rigid panels. Their design is illustrated schematically in Fig. 5. The panel consists of a thin, Aramid fiber re-enforced sheet. It is thus closely based on the Eurostar 3000 AOCS flap, which already has an extensive space heritage. Carbon black included in the resin serves as protection of the Aramid fiber against ultraviolet (UV) light. For the use as cell support in the NGSA application it is strengthened through additional corrugations in a frame like configuration, which provide the required stiffness in deployed configuration. In addition the corrugations act as interface point for deployment hinges. As illustrated in Fig. 5, these corrugations divide the panel in three approximately equal areas.

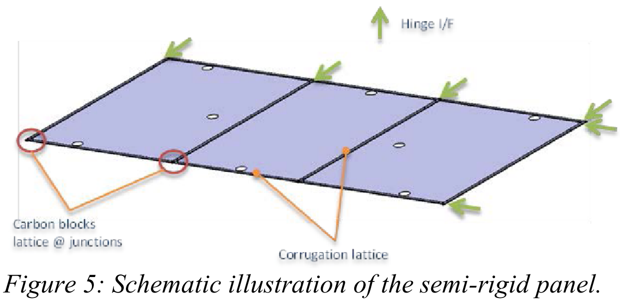

Figure 5: Schematic illustration of the semi-rigid panel.

The damping system, which was developed to substitute the air damping, consists of two main elements. The first one is focused onto the corrugations and prevents the in plane movement of the semi-rigid panels within the stack. The second part of the damping system limits the amplitude the sheet can perform in the area between the corrugations.

As pointed out before, for a complete verification, also the part of the launch with virtually no atmosphere has to be simulated on ground. Rather than attempting to house a conventional shaker in a vacuum vessel, a unique, lightweight vacuum enclosure was developed that can be mounted on a standard shaker. To balance the atmospheric pressure while still keeping the weight down, plates in sandwich configurations were devised. In addition, the size of the test specimen was limited to one third of a semi-rigid panel. This greatly helped to reduce the loads the sandwich plates have to withstand due to the atmospheric pressure. Nevertheless, the testing of a 1/3 panel is still fully representative, since the boundary conditions at the position of the corrugations are the same everywhere on the panel. The vacuum setup mounted on a shaker is shown in Fig. 6. Its resonance frequency is ≈ 100 Hz and thus outside the range of interest for the actual sine vibration test and the base pressure that can be routinely achieved is 15 mbar.

Figure 6: Setup for sine vibration testing under vacuum.

Several 1/3 panel semi-rigid flaps were built and equipped with mass dummies as well as 80 SCAs consisting of 80µm solar cells and 100 µm cover glasses. Sine vibration testing with one up to three semi-rigid panels sandwiched between two rigid panels were carried out under vacuum. The input levels for the three axes were identical to the testing performed in air. In all cases the cell integrity during the dynamic loading could be experimentally verified. Thus the feasibility of the hybrid array concept is validated under all environmental conditions.

In Fig. 7 the readings of one accelerometer on the semi-rigid panel are plotted during an out of plane sine vibration test in a stack consisting of one semi-rigid and two rigid panels. Two main resonances around 23 Hz and around 45 Hz are visible. The first one can be attributed to the semi-rigid panel itself, whereas the second one belongs to the rigid panels, as confirmed by accelerometer measurements on the rigid panels themselves. The appearance of this second peak is an

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indirect consequence of the damping system that was incorporated into the design. While the semi-rigid panels can still oscillate freely, as shown by the presence of their resonance frequency, they are nevertheless coupled to the rigid panels and thus the rigid resonance frequency is visible in the acceleration response of the semi-rigid panels as well.

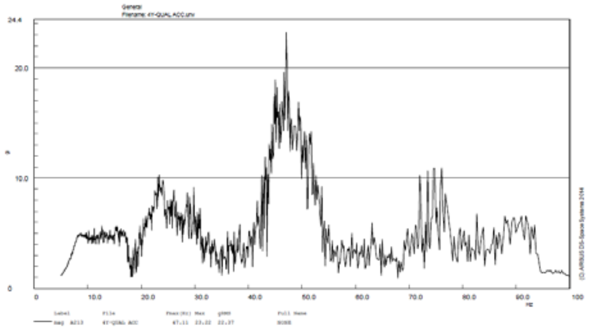

Figure 7: Measured accelerations on a semi-rigid panel during a sine vibration test in vacuum.

The second main consideration for the semi-rigid panels is their strength and stiffness in deployed configuration and, since this is going to be the limiting case, during deployment. The NGSA design uses C-Spring hinges, one at every one of the four corrugations, due to the low mass and the simplified wing integration which is possible with this solution. In order to not overly complicate the overall deployment mechanism, the lateral semi-rigid panels are to be deployed freely. The loads introduced into the corrugations, especially during latch-up, have to remain within acceptable limits.

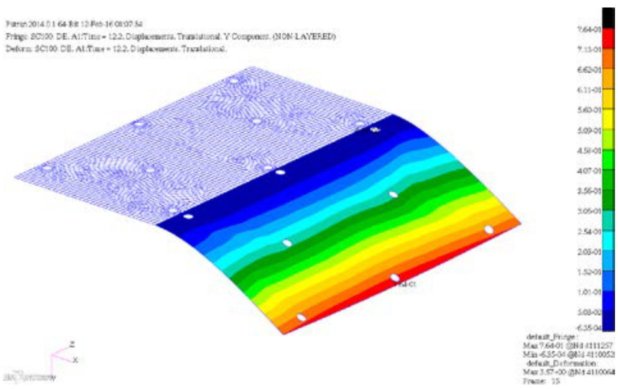

Figure 8: Resulting deflection of the semi-rigid panel during free deployment according to FEM modelling.

To address this topic, a non-linear FEM model was setup and correlated based on the bending curve of the corrugations alone in a 1 g environment. The resulting deformation of a lateral semi-rigid flap during free deployment is illustrated in Fig. 8. The deformation of the outermost edge of the ≈ 2 m wide flap is ≈ 0.8 m, which results in a fully acceptable radius of curvature.

In addition, the maximum bending moment in the corrugations is far below the critical moment. This demonstrates that the planned free deployment of the lateral panels is feasible.

4. PVA CONSIDERATIONS

While from a mechanical viewpoint the semi-rigid panel is the most important element of the NGSA, from the electrical side it is the solar cell assembly.

The NGSA solar array is ideally suited to make maximum use of the next generation of III-V solar cells, which will reach efficiencies above 30% through the addition of subcells and a current matched design. Several of the new cell concepts will automatically result in thin and thus lightweight solar cells. Alternatively cells relying on a Ge bottom cell can be thinned to the desired weight. Within Europe the 4G32 solar cell is under development, with a target efficiency of 28.5 % at 10^{15} 1 MeV e-/cm^2.

As pointed out in Table 1, the SCA mass has a significant impact on the power/mass ratio. The need to have an as lightweight SCA as possible, however, has to be balanced with the radiation shielding requirements. Electric orbit raising (EOR) is a major trend for GEO satellites. Due to the significant mass savings on platform level and the reduce launch cost resulting from it the majority of GEO satellites will employ electric propulsion.

For electric orbit raising missions the radiation dose is significantly increased, due to the additional non-ionizing dose inflicted predominantly by protons in the inner Van Allen belt. This inner belt is crossed multiple times in electric orbit raising trajectories in comparison to only once in a chemical transfer. The expected radiation dose will vary significantly in actual missions, depending on the launcher chosen. One challenge for the PVA layout will be to find an optimal solution for the bulk of the EOR missions, while still ensuring sufficient voltage for the worst case missions. This necessitates an electrical layout that makes use of the non-ideal fill factor of a section by placing the fixed bus voltage in the “knee” of the I-V curve. In this region, voltage can be essentially traded for current.

The expected 1 MeV electron fluence for a typical EOR +GEO radiation environment is plotted in Fig. 9 as a function of frontside shielding. An infinite backside shielding was assumed in this calculation. Therefore the contributions of both sides have to be added to calculate the total dose. As indicated by the blue lines in Fig. 9, the dose shielding curve can be approximated linearly with two slopes. Both lines cross at approximately 130 µm equivalent Si shielding. This represents the

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minimum amount of shielding that should be present both on the front as well as on the rearside. Additional shielding then can be distributed on front or rearside as seen fit. For the NGSA SCA, a 100 µm coverglass has been chosen, which comes fairly close to this minimum shielding requirement. For a Ge based current matched cell, the question arises how much Ge can be assumed as "inactive" and thus as part of the rearside shielding. Assuming an active Ge thickness of 20 µm, the shielding of the inactive Ge, rearside metallization adhesive and semi-rigid substrate amounts to 175 µm equivalent Si shielding thickness for a 50 µm Ge based cell. For such a cell the total equivalent 1 MeV e-fluence amounts to 1.8×10^{15} e-/cm^2. For typical III-V multijunction cells, such a fluence is already in the steep part of the cell degradation curve. For this reason, an 80 µm equivalent Ge thickness was chosen as baseline cell for the NGSA in EOR missions. The mass of such a cell is still compatible structurally with the semi-rigid support, while at the same time the additional 30 µm in rearside shielding on the semi-rigid flaps result in an additional ≈1 % in absolute cell efficiency at end of life.

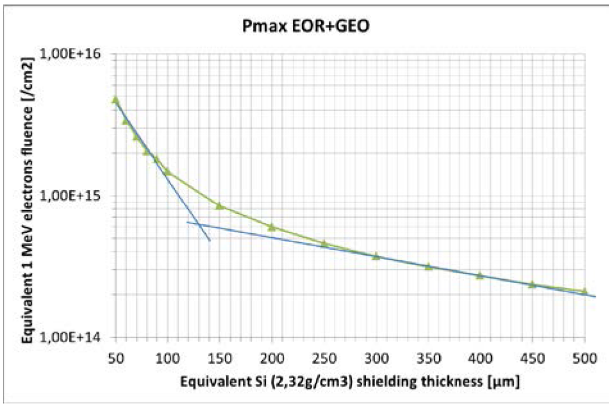

Figure 9: Equivalent 1 MeV P_{max} electron fluence for a combined typical electric orbit raising (EOR) and GEO radiation environment as a function of frontside shielding thickness. Infinite backside shielding was assumed.

5. NGSA IMPLEMENTATION ON EUROSTAR NEO

For Eurostar NEO the NGSA concept will be implemented for the first time, based on a family of 4 rigid and up to 4 semi-rigid panels. The largest version is illustrated in Fig. 10. In this configuration a maximum of 2 semi-rigid panels are sandwiched between two rigid panels each. A double yoke is included to prevent antenna shadowing completely, whereas the innermost rigid panel without side panels facilitates a wider viewing angle of the star sensor. In the baseline configuration, all rigid panels will be equipped with 6x12 cm^2, 140 µm thick triple junction cells and all semi-rigid panels with 80 µm thick 4x8 cm^2 four junction cells. The resulting performance figures are summarized in Table 2.

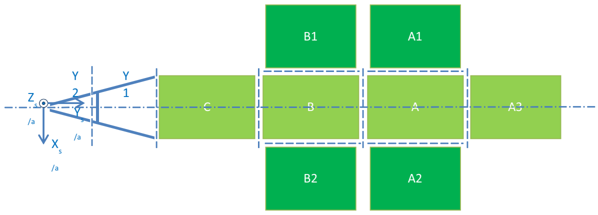

Figure 10: NGSA configuration for the Eurostar Neo platform.

In comparison with Table 1 it is evident that the Eurostar Neo array exploits to a great deal the lower stowage volume provided by the NGSA concept. In addition in a high power version, where the entire array is equipped with 4G32 cells, the maximum end-of life power is increased by an additional 2 kW to ≈ 27 kW and the power/mass ratio is increased to 88 W/kg, a 35% improvement compared to a Eurostar 3000 array.

Table 2: Eurostar Neo implementation of the NGSA.

version	E NEO R4S4 LARS / 4G32	E NEO R4S4 4G32
cell	6x12 cm^2 LARS 26.5%, 4x8 cm^2 4G32 28.5 %	4x8 cm^2 4G32 28.5 %
cell (Ge) thickness	140 µm & 80 µm	80 µm
coverglass	100 µm	100 µm
equivalent fluence (Pmax)	1.5×10^{15}	1.5×10^{15}
power [kW]	24.6	26.6
mass [kg]	314	302
stack height [mm]	264	264
power/mass [W/kg]	79	88
power/volume [kW/m^3]	6.4	7

6. CONCLUSION

The NGSA technology provides an attractive solar array solution for even the highest power GEO telecommunication spacecraft, both in terms of mass as well as stowage volume. It is ideally suited to exploit the benefits of the next generation of lightweight four junction solar cells. Compared to conventional in-line rigid arrays power/mass and power/volume can be doubled. This improvement is achieved through an evolutionary concept with extensive space heritage in all major components like the rigid backbone or the semi-rigid substrate.

Through changing the rigid/semi-rigid panel ratio and through the cell selection in terms of weight and form factor it is possible to tailor the array to the needs of a particular platform to find the optimum solution in terms of power, mass, stowage volume and cost. This was demonstrated for the Eurostar Neo platform. The

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associated solar array will be the first NGSA array to be launched. It will be among the first arrays to fly > 30% four junction cell technology for telecommunication applications.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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