

The Damper Spring Unit of the Sentinel 1 Solar Array

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Abstract

The Damper Spring Unit (DSU, see Figure 1) has been designed to provide the damping required to control the deployment speed of the spring driven solar array deployment in an ARA Mk3 or FRED based Solar Array in situations where the standard application of a damper at the root-hinge is not feasible. The unit consists of four major parts: a main bracket, an eddy current damper, a spring unit, an actuation pulley which is coupled via Kevlar cables to a synchro-pulley of a hinge. The damper slows down the deployment speed and prevents deployment shocks at deployment completion. The spring unit includes 4 springs which overcome the resistances of the damper and the specific DSU control cable loop. This means it can be added to any spring driven deployment system without major modifications of that system. Engineering models of the Sentinel 1 solar array wing have been built to identify the deployment behavior, and to help to determine the optimal pulley ratios of the solar array and to finalize the DSU design. During the functional tests, the behavior proved to be very sensitive for the alignment of the DSU. This was therefore monitored carefully during the qualification program, especially prior to the TV cold testing. During TV "Cold" testing the measured retarding torque exceeded the max. required value: 284 N-mm versus the required 247 N-mm. Although this requirement was not met, the torque balance analysis shows that the 284 N-mm can be accepted, because the spring unit can provide 1.5 times more torque than required. Some functional tests of the DSU have been performed without the eddy current damper attached. It provided input data for the ADAMS solar array wing model. Simulation of the Sentinel-1 deployment (including DSU) in ADAMS allowed the actual wing deployment tests to be limited in both complexity and number of tests. The DSU for the Sentinel-1 solar array was successfully qualified and the flight models are in production.

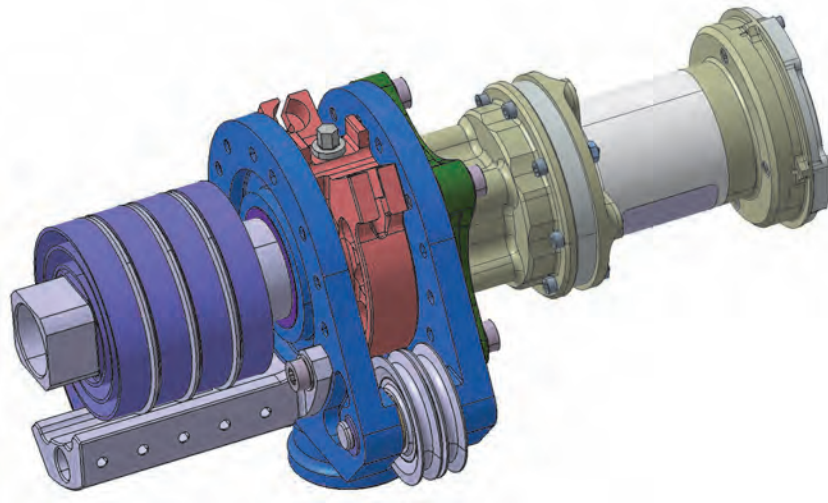


Figure 1: Damper Spring Unit.

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Introduction

The Damper Spring Unit (DSU) is part of the deployment system of the Sentinel 1 Solar Array (SA), an ARA Mk3 product family solar array from Dutch Space. Sentinel-1 is an imaging radar satellite aimed at providing continuous all-weather, day-and-night imagery for monitoring sea ice zones and the arctic environment, surveillance of marine environment and monitoring land surface motion risks, mapping of land surfaces: forest, water and soil, and provide mapping in support of humanitarian aid in crisis situations. The function of the deployment system is to deploy the Sentinel 1 SA wing from the folded panel stack (stowed configuration) mounted on the S/C side wall to the deployed configuration (see Figure 2). The DSU is designed to provide the damping required to control the deployment speed of the spring driven solar array in situations where the standard application of a damper at the root-hinge is not feasible. The large number of power harness cables of the Sentinel 1 SA prevents the location of the damper at the root hinge. This paper gives a description of the damper spring unit and its functioning in the Sentinel 1 deployment system. The qualification program of the DSU is discussed, the torque balance analysis and deployment analysis in ADAMS, which is required to qualify the use of the DSU in the Sentinel 1 deployment system.

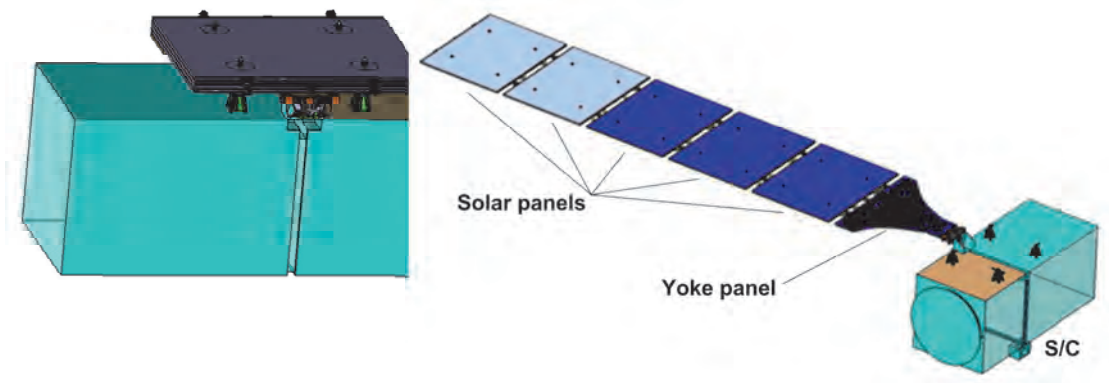


Figure 2: Sentinel 1 solar array wing (stowed and deployed configuration).

Sentinel 1

The DSU will be first applied in the Sentinel 1 solar array wing. The wing consists of 6 panels; 5 solar panels and a yoke panel. It is fixed to the spacecraft via 4 hold down stacks, each containing 2 Thermal Knives to cut the hold down cable inside the hold down stack (see Figure 2 and Figure 3). The deployment system of the Sentinel 1 SA consists of:

- Twelve (12) panel hinges per wing (i.e. two hinges per hinge line). Each hinge has a pre-tensioned spring to deliver the hinge line torque for deployment and a locking device.
- A deployment synchronization system which consists of pulleys, guide-blocks and cables to control the deployment. A system of Kevlar synchronization cables are connected via pulleys to the panel hinge assemblies. These cables synchronize the panel motion between all panels.
- The damper-spring-unit, mounted on the yoke panel front side (at sun side in deployed condition and between yoke panel and spacecraft side wall in stowed condition) and coupled via Kevlar cables to the synchro-pulley of a dedicated DSU hinge at hingeline 2 (see Figure 4).
- Kick-off-spring-unit attached on the yoke panel and connected with the root hinge synchronization pulley to support a compact first stage 90° deployment.

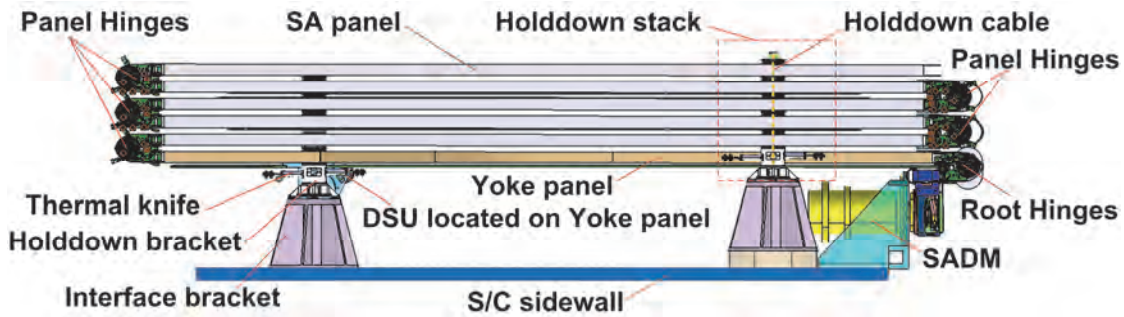


Figure 3: Sentinel 1 stowed solar array wing (side view).

The Sentinel 1 solar array deviates slightly from standard ARA Mk3 solar array designs mainly in respect with the deployment movement from stowed to the deployed configuration. The root hinge must deploy over 180 degrees, but more important, the trajectories of the C.O.G.'s of all panels have to be confined to a limited area which requires a two stage deployment movement of the panels which is shown in Figure 5. The synchronization system controls these 2 phases in a continuous way avoiding interference with S/C structure. The Sentinel 1 deployment design is a passive system as the traditional deployment system with the same design of hinges, motoring springs, synchro-cables and eddy-current deployment damper. The root hinges pulleys are, however, specifically designed eccentric and the routing of the cables is adapted. The deployment of the panels starts immediately after the last hold down cable has been cut. The deployment motion is driven by the kick-off spring on the yoke panel and the deployment springs mounted at the root hinge and at the panel hinges. The eccentric roll-on / roll-off pulleys on the root hinges realize a gradually increasing synchro-cable movement. The cable payout up to 90 degrees hinge line rotation is small, thus the panels will stay approximately stacked up to about 90° opening of the root hinge line (phase 1). In phase 2 the root hinge opens from about 90 to 180 degrees, while all other hinges open in a synchronized manner up to deployment completion (from about 5 to 180 degrees). This sequence ensures that the CoG travel and Mol shift – and therefore the disturbances on the spacecraft's attitude - are minimized. At the end of the deployment each individual hinge will latch to assure a stiff deployed configuration.

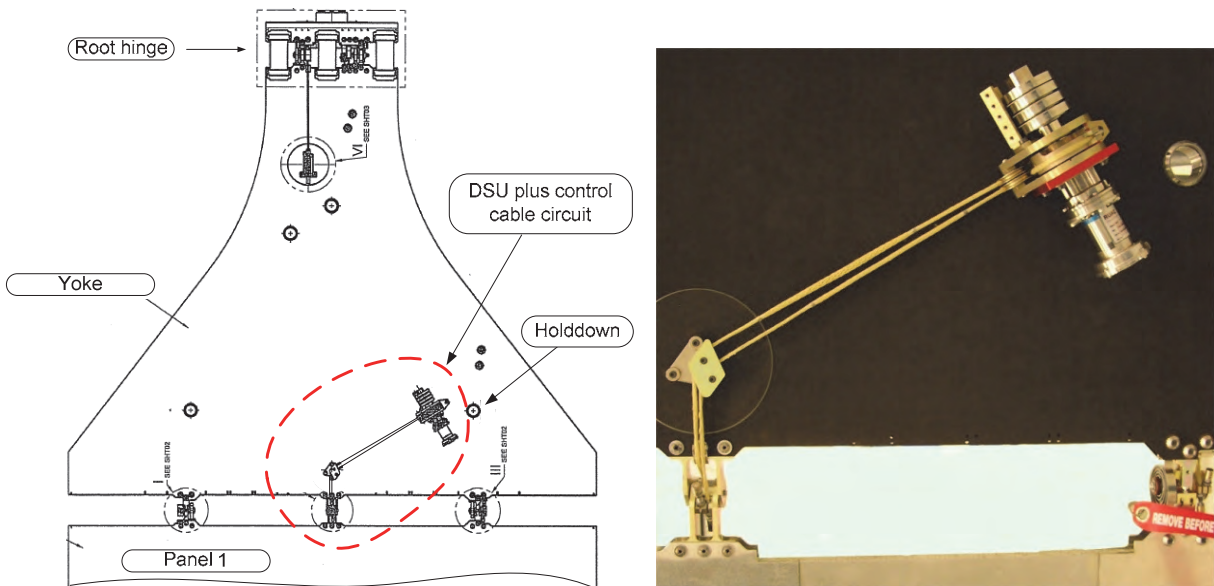


Figure 4: The DSU position at the Sentinel 1 solar array.

Sentinel 1 Engineering Model

Using engineering models helped us to identify the behavior of the two stage deployment system and how the DSU functions within this system (see Figure 5). Due to the severe thermal environment, some flexibility of the synchronization system is required. This flexibility also introduces unwanted non-synchrony. Design modifications are introduced to minimize these effects. As the DSU is not directly integrated in the synchronization system, its pulley can be increased or reduced in diameter. This change can introduce a more favorable ratio between the various pulleys and thus limit the non-synchrony effects of the flexibility. Unfortunately these effects cannot be eliminated completely, which means it has to be accounted for in the deployment analysis of the system. After the final pulley ratio was identified, the DSU design could be finalized.

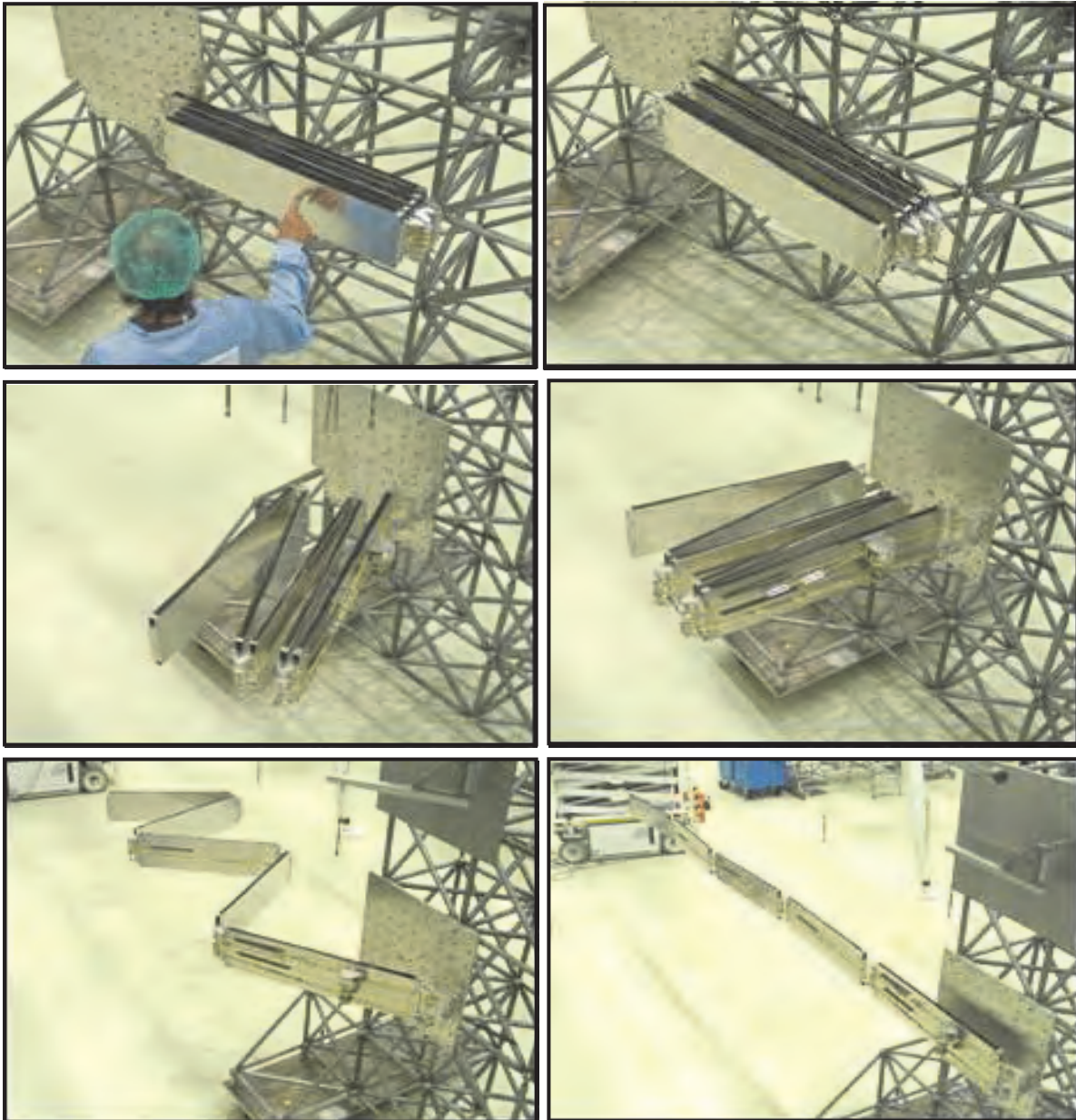


Figure 5: The deployment of the Sentinel 1 engineering model.

Damper Spring Unit description

The Damper Spring Unit consists of 4 major parts (see Figure 6):

- The main bracket, which supports all other parts of the DSU and allows fixation to the Solar Array. The main bracket interface with the solar array is dedicated per project. The Sentinel 1 DSU is fixed with a M4 into a blind insert and a M8 bolt which interfaces with an adapted cup-cone bracket, see Figure 7.
- The spring unit, which includes 4 standard ARA Mk3 root hinge actuation springs, to counter the retarding torque of the specific DSU control cable loop and the eddy current damper start-up torque with sufficient factor of safety.
- The actuation pulley, which is coupled via Kevlar cables to a synchro-pulley of a hinge of the solar array (see Figure 9).
- The damper is an eddy current damper supplied by RUAG Space AG, Zurich, Switzerland. The damper consists of three basic modules:
 - A high efficiency damper unit which is a self-contained module with its own shaft supported by its own set of bearings. The damping is generated with a high purity copper disc rotating within a highly concentrated magnetic field. The field is provided by 12 pairs of samarium-cobalt magnets. The damping rate can be varied. The different damping rate levels depend on the relative orientation of the magnet pairs which can easily be set by rotating the ECD end cover.
 - An intermediate gear-head is employed based on a standard planetary unit. This unit provides the first stage of torque amplification.
 - The input stage is the second torque amplification stage and provides a further amplification ratio. This stage is designed to accommodate high torque levels (up to 100Nm).

The damper is currently qualified to provide a damping rate between 500 and 1700 $\text{N}\cdot\text{m}\cdot\text{s}/\text{rad}$ at operational temperatures of -55 to $+100^\circ\text{C}$. A dedicated attachment plate is required to attach the damper to the main bracket.

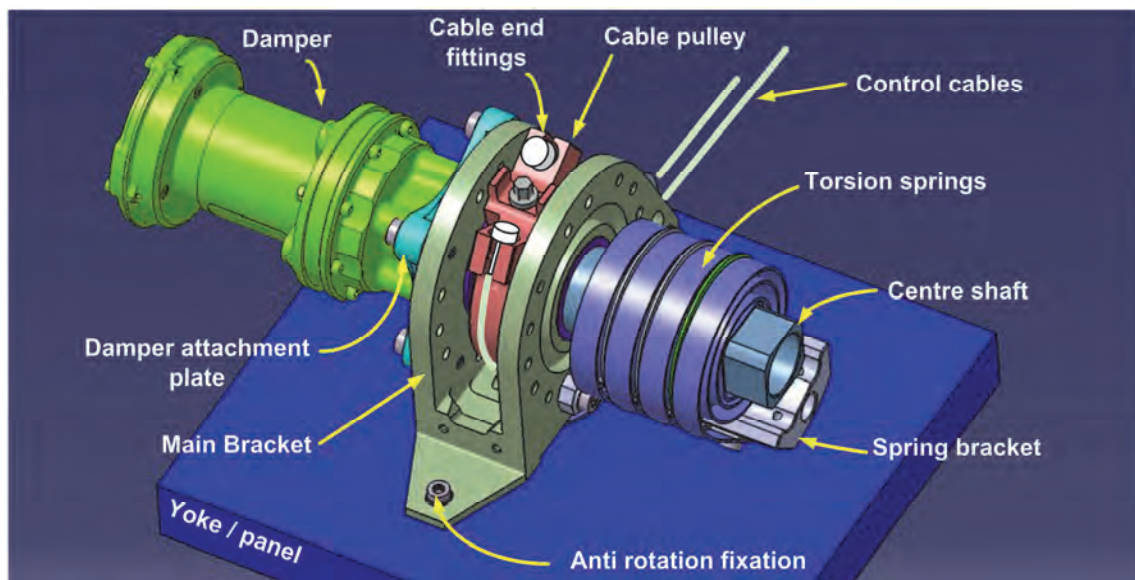


Figure 6: Damper Spring Unit parts.

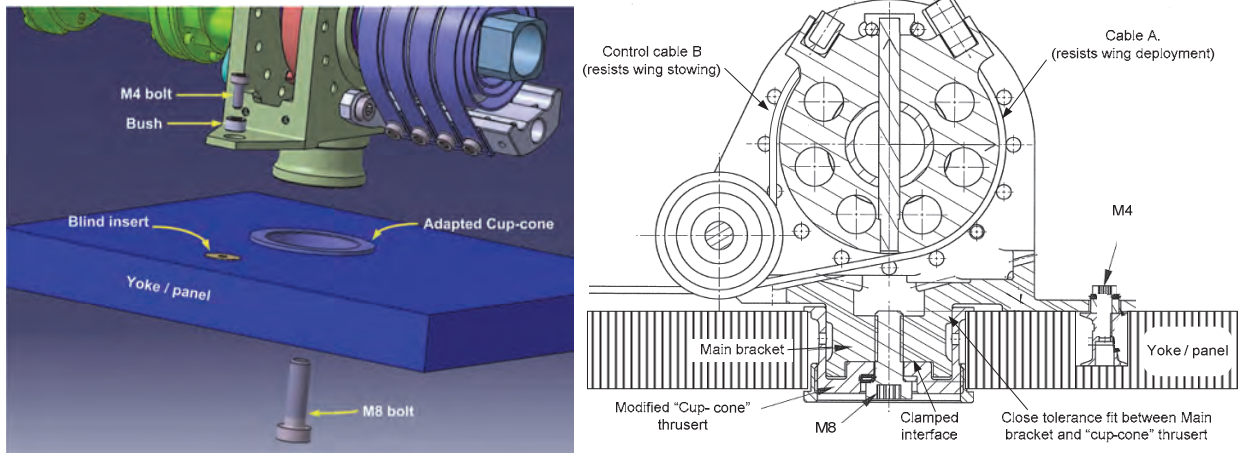


Figure 7: Damper Spring Unit interface.

Due to the heavy cable loads typical for a DSU application a new cable end fitting has been designed and qualified. The Kevlar cable is a standard ARAMk3 / FRED cable type of which the fitting is changed from a single knot in a cylindrical bush into a spike in a conical receptacle (see Figure 8). Both DSU cables contain a preload spring. The design of the preload spring depends on the routing of the synchro-cable. For the Sentinel 1 DSU cable route a preload spring with a preload of 5N has been adopted. This value is an important aspect in the torque balance of the unit as a whole and should be analyzed carefully. The torque balance analysis is described later in this paper. Figure 9 shows the interfaces of the DSU cables.

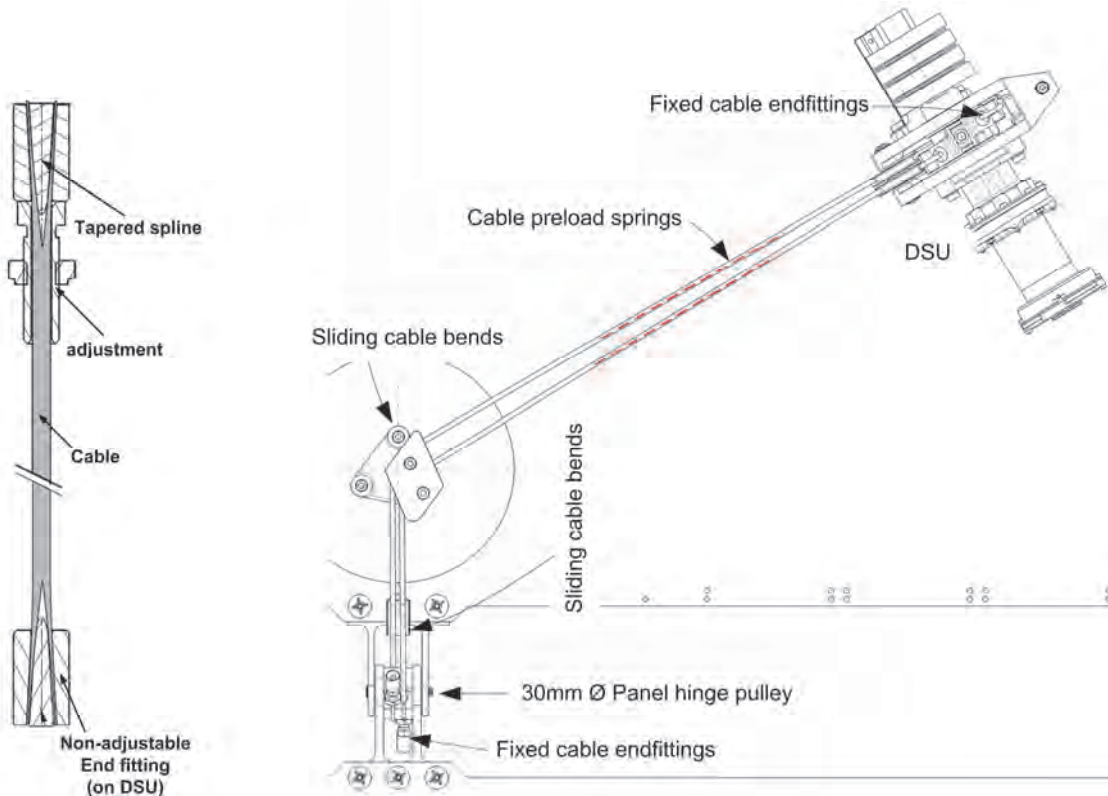


Figure 8: DSU control cable design.

Figure 9: DSU control cable interfaces.

The Center shaft design is less straightforward as one would expect due to the thermal environment requirements and the variation in thermal coefficient of the damper stainless steel input shaft and the aluminum 7075 Center shaft. The damper has a steel input shaft unlike the Center shaft, the main bracket and the cable pulley, which are of aluminum. An additional stainless steel shaft, the damper engagement shaft is introduced to interface with the damper input shaft and the Center shaft. The damper engagement shaft is coupled with the Center shaft by the lock bolt shown in Figure 10.

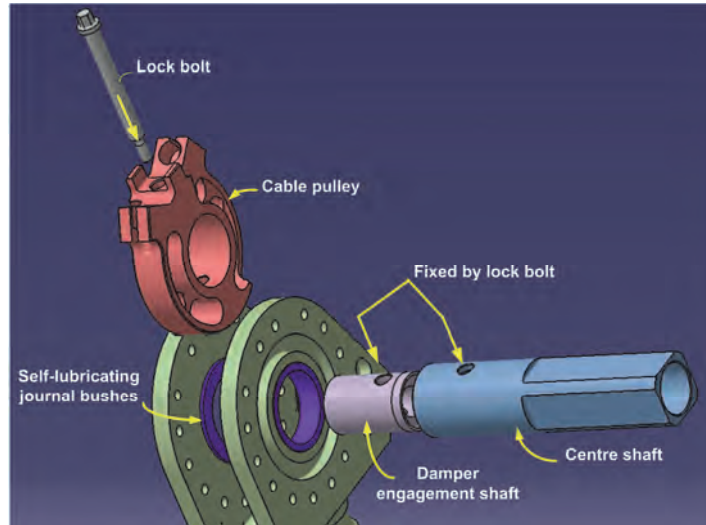


Figure 10: Damper Spring Unit shaft design.

Qualification program

The qualification program consisted of various functional tests at ambient and at the extreme temperatures (-115°C / +115°C), static load tests, random- and sine-vibration tests and a life test. As the damper has been qualified by RUAG, not all tests are performed with the damper attached to the main bracket. This allows a full characterization of the DSU, which is required to create the ADAMS model. Figure 11 gives the test sequence of the DSU, which indicates when the damper was not used.

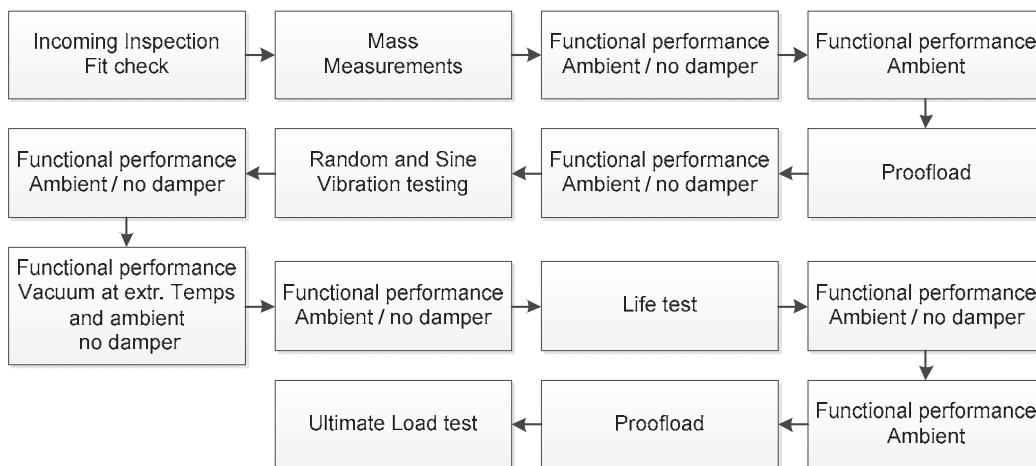


Figure 11: DSU qualification test sequence.

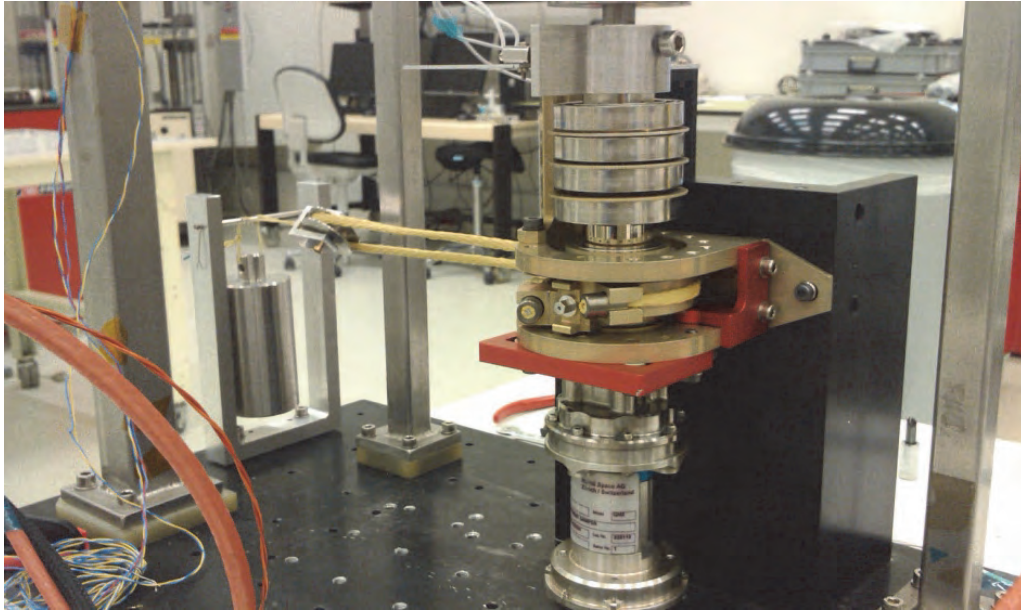


Figure 12: Functional test of the DSU qualification model (ambient).

Random vibration tests have been done and the test requirements of Table 1 and 2 have been met.

Table 1: Random Vibration Test requirements (all 3 axes)

Frequency Range [Hz]	PSD Qualification
10 – 80	+ 6 dB/oct until 0.6 g ² /Hz
80 – 400	0.6 g ² /Hz
400 – 2000	- 6 dB/oct
Overall random vibration level [G _{RMS}]	20
Duration [seconds]	120

Table 2: Sine Vibration Test requirements (all 3 axes)

Frequency Range [Hz]	g-level
5– 22	Maximum shaker amplitude
22 – 100	30

During the functional tests, the behavior proved to be very sensitive for the alignment of the DSU. This was therefore monitored carefully during the qualification program, especially prior to the TV cold testing. During TV “Cold” testing the retarding torque exceeded the max. required value: 284 N-mm versus the required 247 N-mm. This requirement had been set conservative and fortunately the torque balance analysis shows that the 284 N-mm is acceptable. Because this Non Conformance has been resolved and all other pass/fail criteria are met, like the ultimate load of cable A of 3360 N, the DSU qualification test program has been successful and the DSU design is qualified for use within the specified environment (temperatures, forces and number of on ground cycles).

Torque Balance Analysis

The torque balance analysis presented here shows the torque balance for the critical situation of the deployed position during cold deployment. In the cold condition the friction coefficients and the damper retarding torque are at their highest, and the deployed position has the lowest available DSU drive spring torque. Figure 13 shows the torque balance calculation flow and Figure 14 shows which cable forces and deflection angles are taken into account. The torque balance budget for the DSU and its control cables, given in Table 3, shows that the DSU motoring torque is a factor 3.3 higher than the worst case retarding torque. A motoring factor (torque margin) >3 is required, so this requirement is met. The DSU spring unit can provide up to 7400 N-m, consequently a higher motoring factor can be achieved if so desired.

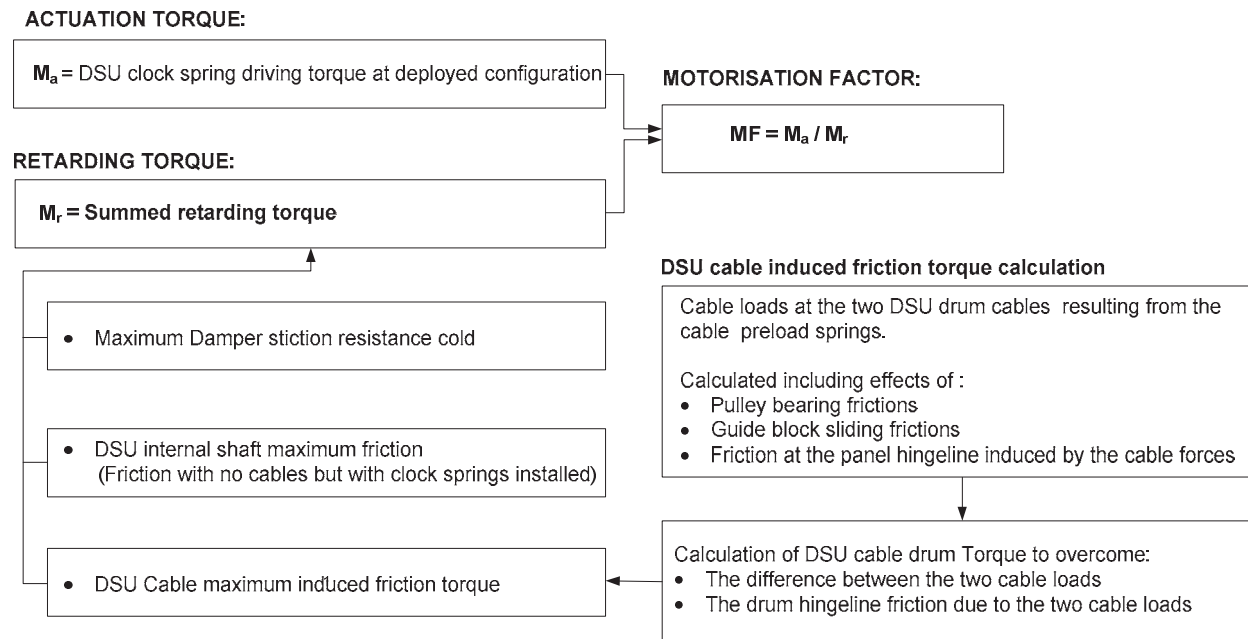


Figure 13: Torque balance calculation flow.

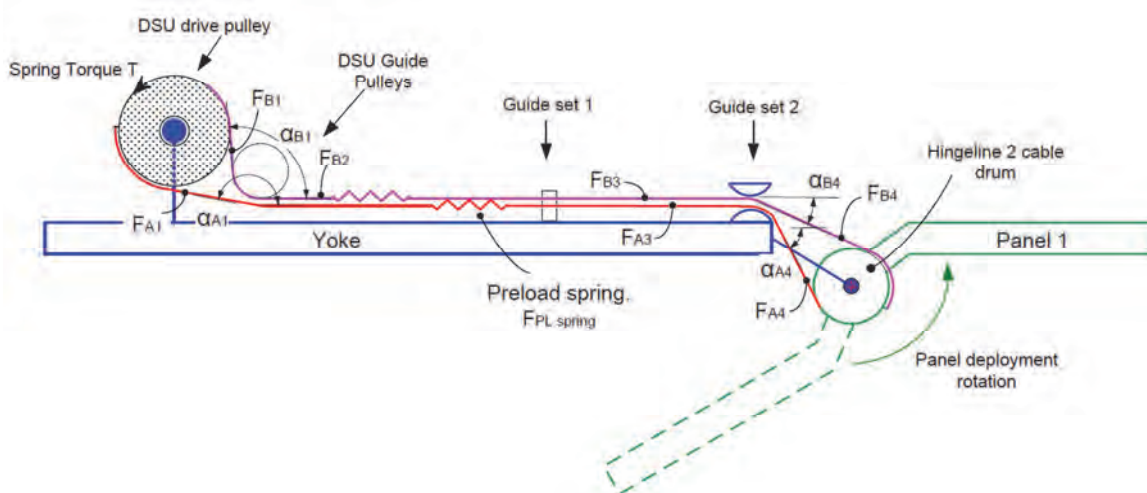


Figure 14: DSU cable forces and deflection angle definitions.

Table 3: The DSU system torque balance budget.

	COLD CASE DEPLOYMENT		
	Torque	Safety	Factored
	[Nmm]	factor	torque
		[-]	[Nmm]
RETARDING TORQUE DSU	DEPLOYED		
damper start torque	-1240	3	-3720
Resistive torque of the DSU shaft + pulleys	-284	3	-852
TOTAL retarding	-1524	3	-4572
TOTAL motoring torque DSU springs	5100	1	5100
Motorization factor	3.3		

Sentinel 1 Deployment Simulation in Adams

The deployment of the Sentinel-1 solar array is studied with the commercial multi-body package ADAMS which is part of the mechanical engineering software of MSC. In ADAMS, a model of a solar array wing is characterized by Parts, Joints and Loads. The ADAMS Sentinel 1 model is shown in Figure 15.

The parts in the model description are:

- Panels: the yoke panel and the solar panels.
- Synchronization system: pulleys, guide-blocks and begin and end parts of the synchronization cable.
- The damper unit

The constraints in a solar array wing model define:

- revolute joints (or hinges) between the panels
- Constraints relating two markers that together define a marker for the (virtual) synchro-cable (The contributing load is implemented and a graphical element. No actual body is representing the cable)
-

The loads in the model are:

- Deployment torques, consisting of
 - Torques to deploy the stack of panels
 - Kick-off spring which pushes the complete stack during the first 60 degrees of the root hinge
- Non-linear loads to prevent that the hinges between the panels rotate beyond the structural boundaries (The panels are not able to cross each other)
- Linear loads activated when the hinge locks (=at the end of the hinge deployment)
- The damper load applied by the damper
- The loads in the synchronization cables

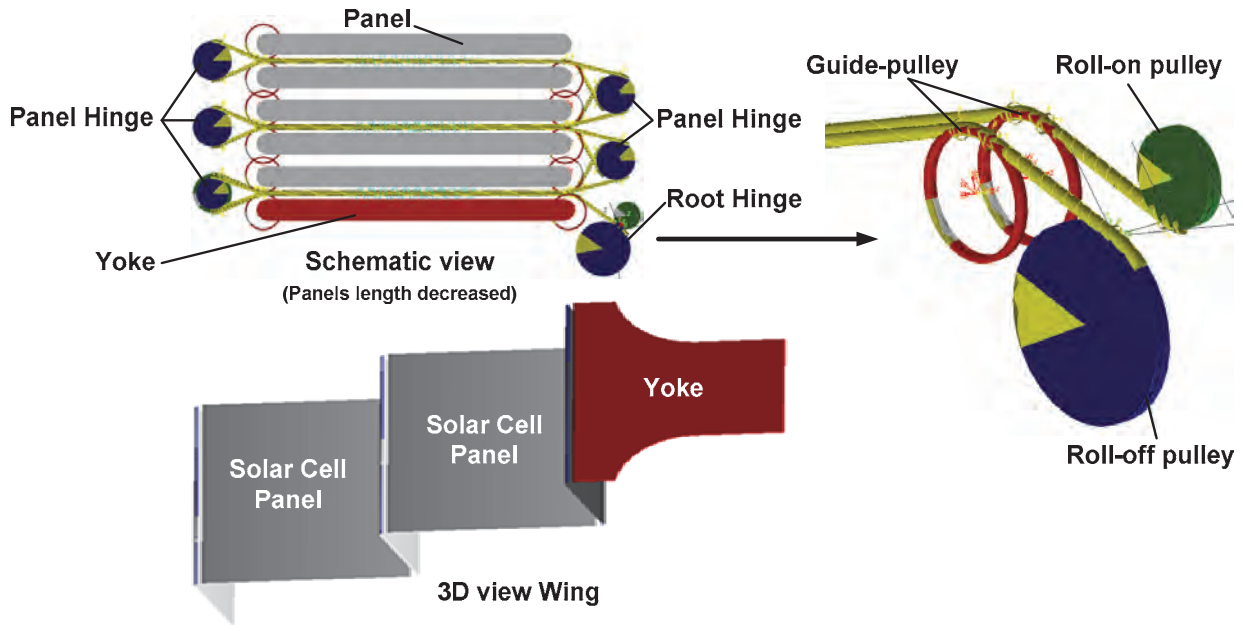


Figure 15: The Sentinel 1 SA wing representation in ADAMS.

The functional components are modeled in ADAMS as User Defined Entities (UDE's). Since the functional components are fully parameterized the UDE's can be re-used in a very efficient way. The actuation springs are straightforwardly represented by moments in the hinges. The characteristic moment – angle behavior is introduced as a prescribed curve. Unfortunately, in ADAMS cables and pulleys are not standardly available and therefore a toolbox developed by Sayfield International has been used. With this toolbox the synchronization system has also been modeled as a UDE with help of sub-models of the pulleys, slip-rings and cables from the toolbox. In these sub-models, the cables are not physically introduced but as forces. The spring damper unit is also modeled with the cable toolbox. Figure 16 shows the complete DSU system: the damper disk, where the damping load is applied, the outer disk, the cables and the pulley. Only the spring unit of the DSU is not shown. The spring is modeled by a moment as a function of the rotation angle of the outer disk.

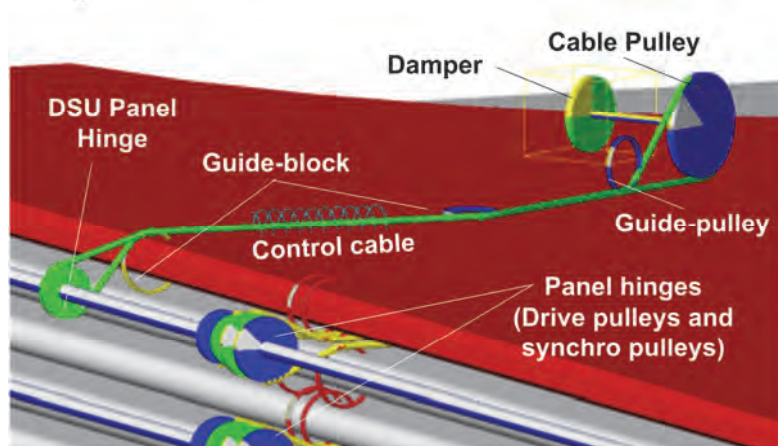


Figure 16: The DSU representation in ADAMS.

The two stage deployment of Sentinel 1 is shown in Figure 17. Such a trajectory is achieved by placing the pulleys off centered and using different sizes for the pulley radii. This adapted design changes the roll-on and roll off characteristics of the cables such that the wing opens approximately as required. This pulley configuration is shown in Figure 18.

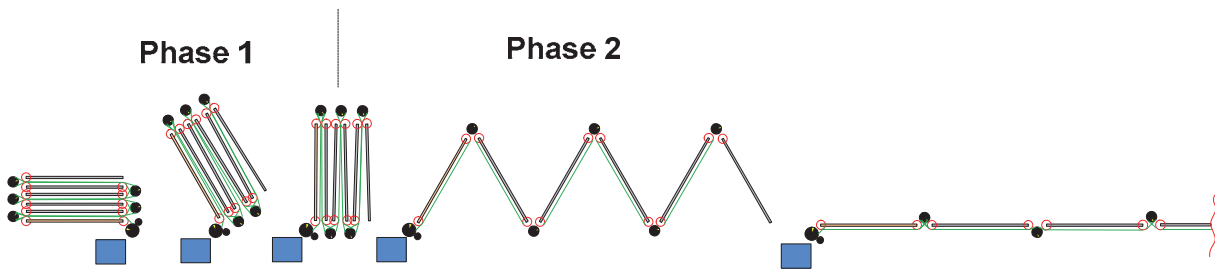


Figure 17: The two stage deployment.

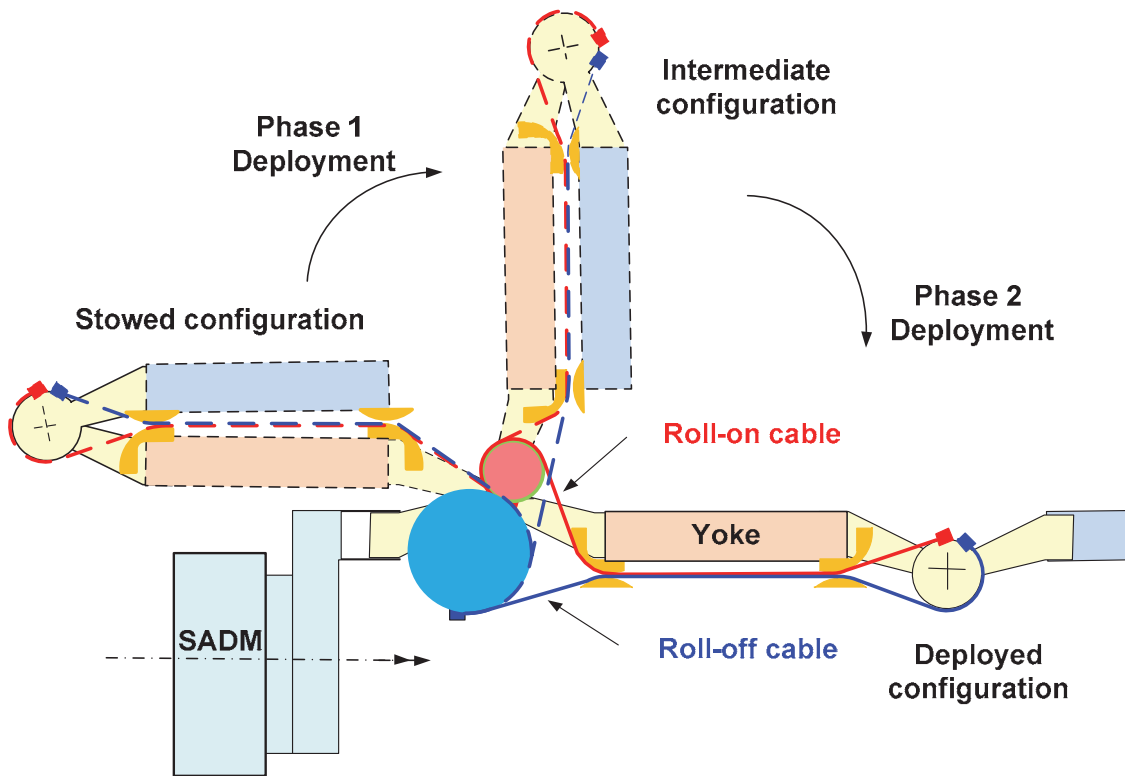


Figure 18: The Root Hinge Roll-off and Roll-on pulley configuration

Figure 19 shows the ideal roll-on and roll off characteristic and the realized characteristic as a function of the root angle. The root hinge pulleys do not display any significant roll-on and roll-off in the first 90 degrees. Because there is no roll-on and roll-off, the next hinge lines are not able to open. The stack opens as a complete package. After about 90 degrees the length of the cables starts to change with the root hinge angle forcing the next hinge lines to follow.

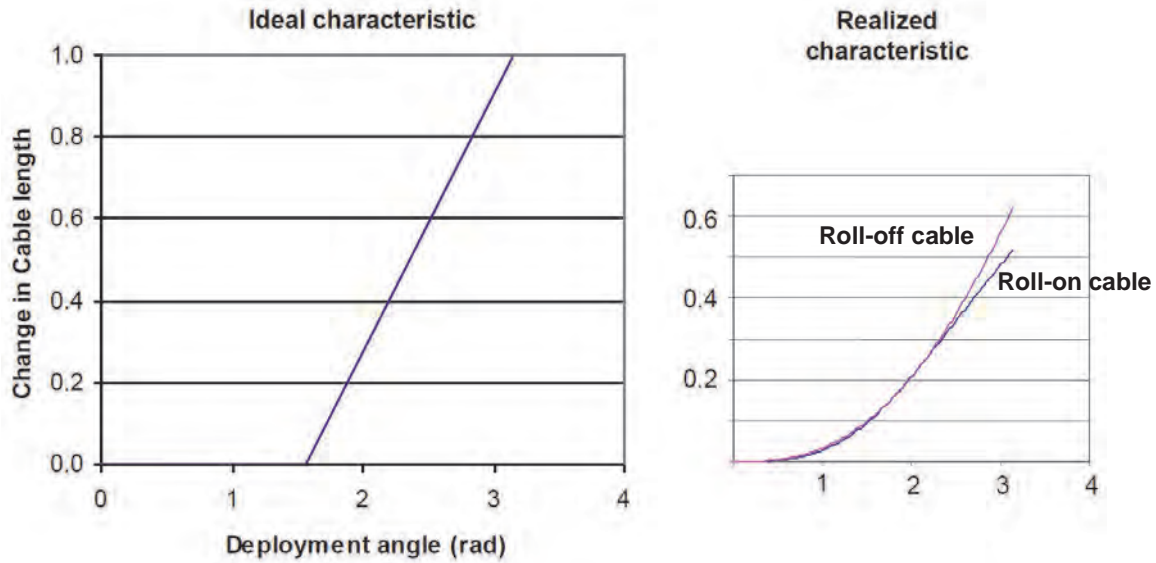


Figure 19: The roll-on / roll-off characteristic.

The parameters in the ADAMS model are now tuned to the baseline Sentinel 1 design including the flexibility of the synchronization system. The model is used to predict the deployment characteristics under various thermal conditions and provides the following output: forces in the synchro-cables and control cables of the DSU, the torque provided by the DSU, shocks in the hinges when they lock, deployment time and path of the wing and the loads at the satellite interface. The ADAMS model is validated with the deployment test results of all relevant units and consequently the ADAMS results could be used to qualify the use of the DSU within the Sentinel-1 solar array (verification of the occurring loads). It showed that the loads and shocks were within specification, the deployment time is within 88 and 284 seconds and deployment path of the Solar Array stays within the allowed deployment volume. Figure 20 shows the panel positions of the SA wing during deployment case 2, which provides maximum forces in the synchronization system.

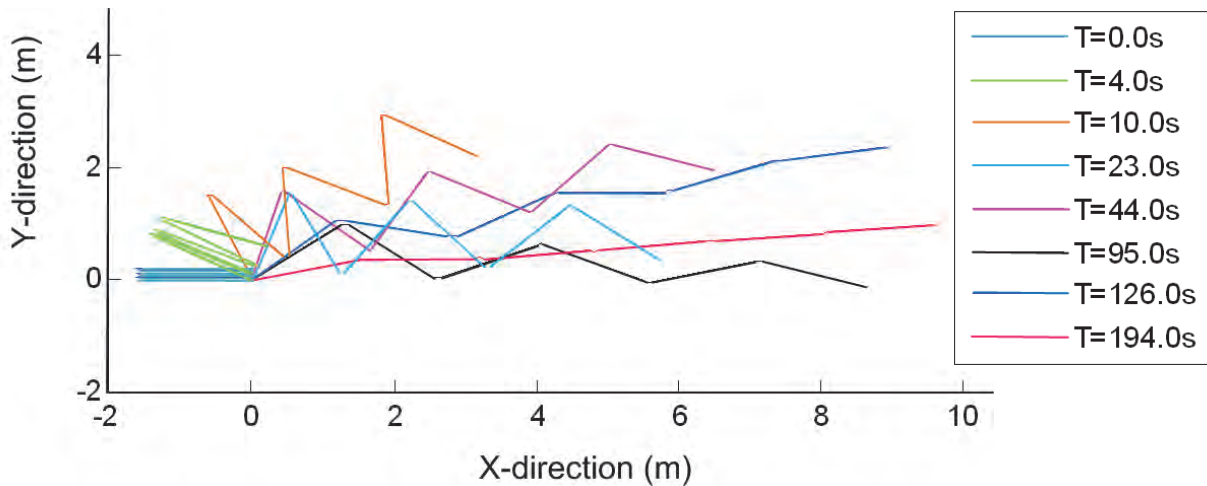


Figure 20: The deployment path of Sentinel 1.

Conclusion

The DSU for the Sentinel-1 solar array was successfully qualified and the flight models are produced (see Figure 21). Using engineering models proved to be essential to identify the deployment behavior of the Sentinel 1 wing and the required pulley diameter of the DSU. The qualification program showed that the alignment of the DSU needs to be controlled carefully to limit the friction of the control cables. The spring unit of the DSU design is over dimensioned for the Sentinel 1 SA; it can provide 1.5 times more torque than required, allowing application of the DSU in less favorable conditions / deployment systems. Representation of the Sentinel-1 deployment system (including DSU) in ADAMS allowed the actual wing deployment tests to be limited in both complexity and number of tests.

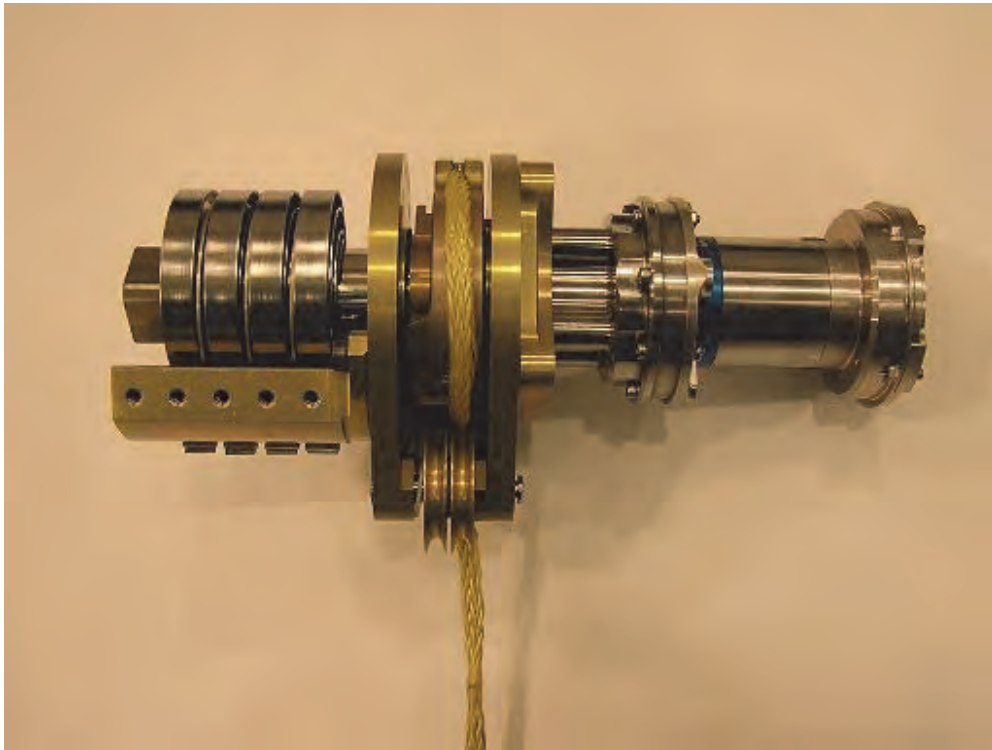


Figure 21: The DSU flight model.

Acknowledgements

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