THE TAPE SPRING HINGE DEPLOYMENT SYSTEM OF THE EU:CROPIS SOLAR PANELS

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1. ABSTRACT AND INTRODUCTION

In the DLR (German Aerospace Center) compact satellite program the satellite Eu:CROPIS - featuring a biological payload – is developed. The cylindrical Satellite of 1m diameter has four deployable panels for power generation. Those panels are connected to the main structure by glassfiber reinforced polymer (GFRP) tape spring hinges. The hinges, comparable to curved metallic measuring tapes, have elastic energy stored when flattened and folded and thus deploy the panels by simply unfolding. When unfolded the hinges snap into their original shape and support the panels with considerable stiffness. No friction or mechanical locking is involved in the deploying process, which increases the systems reliability. Despite all these advantages other design aspects need special consideration. The GFRP needs to be protected against environmental influences like atomic oxygen and heat. Depending on the folded state and the hinge configuration the length of the hinges cannot be chosen freely. The installation process requires consideration as well. While the hinges are very flexible in the folded state they have to be installed quite accurately to be able to snap into their deployed position and fully support the panel.
The presented paper gives an insight into the tapespring hinge deployment system of Eu:CROPIS. Design iterations are explained with the background of the decision making process influenced by the overall satellite configuration, tests and testability, experiences gained during integration and PA considerations. Further details of the manufacturing and integration process are described. The verification concept is outlined and explained. Tests performed for verification or gaining experience are described including the setup and considerations for the tests to be representative.

2. DESCRIPTION OF DEPLOYMENT SYSTEM

The Eu:CROPIS compact satellite has four panels of 0.8m² each that provide power to the satellite. During launch these panels are folded to the sides of the satellite (stored configuration, Fig. 1). In Orbit the panels are deployed to form a plane in a windmill configuration with the satellite in the center (deployed configuration, Fig. 2).
In the stored configuration each panel is connected to the satellite by just 2 bolts, which can be released by TiNi frangibolt mechanisms [4].

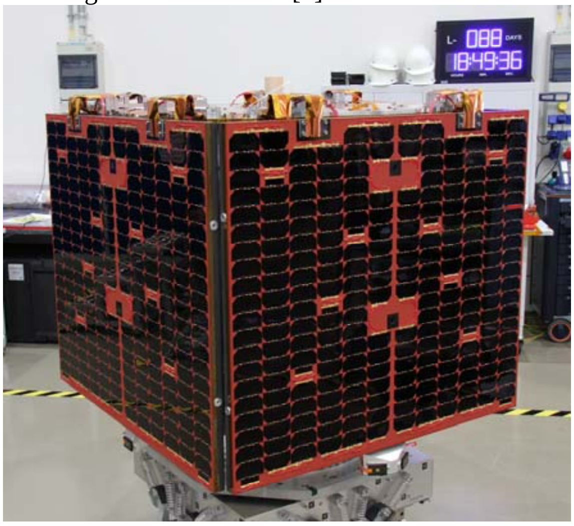


Figure 1. Satellite in stored configuration (flight model)

To obtain a defined bearing the panels are supported by four standoff points (Fig. 3). Each of the connecting bolts is positioned in the middle of two standoffs. The design of this configuration is explained in [6]

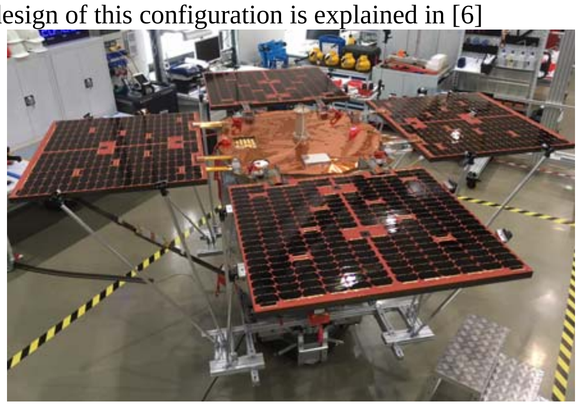


Figure 2. Satellite in deployed configuration (flight model)

Both bolts are required to securely keep the panels in place under launch loads. The separation can be sequentially with one bolt keeping the panel roughly in place. Once the second bolt is released the panels are free to deploy.

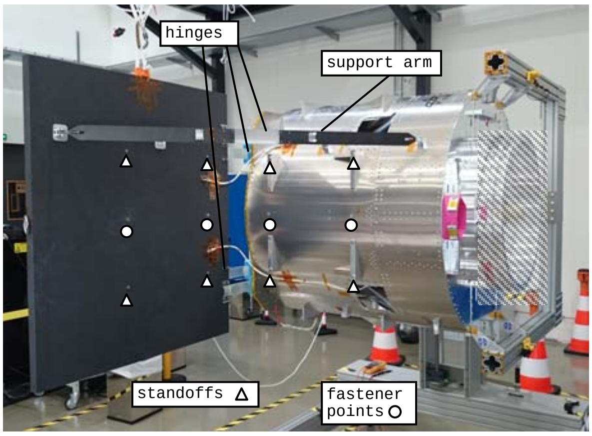


Figure 3. Satellite with one deployed panel (structural model)

The panels are supported by four tape spring hinges and one support arm. The support arm provides some additional stiffness. As the satellite is spin stabilized the rotation can trigger a vibration at the panels. Thus the panels are required to have a deployed natural frequency above the rotational speed of the satellite which is ensured by the supporting arm.

2.1. Deployment System

After the release the panels are deployed by their four tape spring hinges and the support arms (Fig. 4). The support arms themselves have a tape spring hinge in the middle to support the deployment and to stabilize the arm in the deployed configuration.

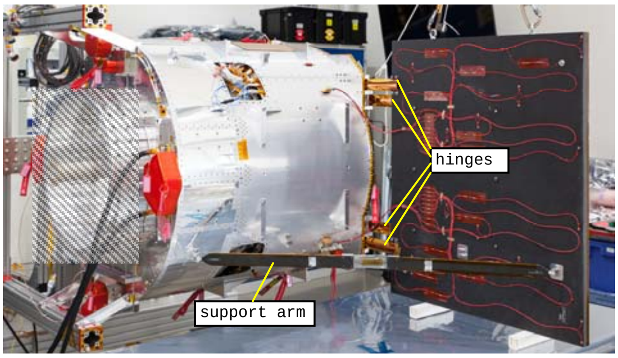


Figure 4. Satellite with one deployed panel (flight model)

The hinges are connected to the upper and lower side of the panel (The upper side being the one with cells). Therefore the bending stiffness of the panel support is not defined by the bending stiffness of the hinges but rather by their axial stiffness. As the panels have a considerable thickness of 31mm the hinges are able to support the panels statically under earth gravity.

2.2. Tape Spring Hinges

Unlike conventional hinges the tape spring hinges principle is based on elastic deformation. The tape spring hinges are part circular shaped glass fibre reinforced plastic profiles. The shape gives considerable stability when straight but can be flattened and bend to a great extent. The flattening reduces the bending stiffness in the flattened area by magnitudes (factor 1800 in the given configuration). Once flattened, the hinges can easily be deformed to the stored position. The bending curvature can be oriented in the same or in the opposite direction of the undeformed profile [3] (principle depiction in Fig. 5). Further information about tape springs can be found in [1], [2] and [5].

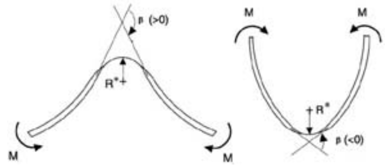


Figure 5. folding of a tape-spring with and against the curvature of the undeformed profile [3]

Curvatures in the opposite direction have a higher elastic torque. Where bended the hinges keep their flattened profile. It behaves like a thin belt of GFRP. This flattened area can be located anywhere along the hinges length. Only at the very end of the hinge the curvature can lead to cracks, if the profile is fixed.

When released the hinges deploy the panels with moderate torque. Once the hinge straightens out it pops into the original curved profile and thus regains a higher stiffness along its length.

Therefore the tape spring hinges perform all conventional tasks of a deploying hinge in just one piece, hinge, elastic energy for deployment and locking.

There are also differences present. The tape spring hinges do not provide a defined hinge axis. Also they do not provide an indication for the mechanical locking.

The hinges are made from glass fibre interglas 92125 and Lange&Ritter LH160/LR162 resin. Interglas 92125 is a koeper woven fabric of 280g/m².A peel ply is not used to avoid a textured surface with possible crack initiation (note that in earlier tests peel ply was used which is visible on the hinges on some figures (e.g. Figure 7) used here).

Glass fiber is chosen because of their high ability to bear elastic energy, thus the product of allowable strain and stiffness.

The geometrical properties are:

- free length of 140mm
- curvature radius 30mm
- thickness t of 0,25mm
- width of 45mm

In contrary to the high ability to bear elastic energy in deformation GFRP has the disadvantage that the resin is quite sensitive to atomic oxygen (ATOX), temperatures above 100°C and UV-radiation. Single layer insulation is used to protect the hinges against these environmental influences.

2.3. Accommodation and Integration

Tape spring hinges only fixed at their ends can form up to three bends along their length depending on the boundary conditions e.g. distance and angle. Even though they can be easily deformed manually into more

complex bending shapes, once installed and fixed at the ends only, the hinge takes the shape of the lowest potential energy possible. Considering this the configuration must support a bending shape that does not collide with any other part of the satellite and does not overstress the hinges themselves.
Due to the stored and deployed configuration the folded hinges must have a folding angle of 90°. What can be adjusted – within other constraints – is the length of the hinges and the position of the fixation points.
Four hinges are installed on each panel, two on top and two on the bottom. Top and bottom hinges are oriented in opposite direction. Due to the differing orientation and the distance of the upper and lower hinges the deformation in the folded state is significantly different (Fig. 7).
Taken a panel configuration as Eu:CROPIS as an example several parameters influence the folded shape of the hinges. Those are:

- Distance of the panel to the fixation point on the satellite side.
- Position of the panel across the fixation point
- Length of the hinges
- Distance of the hinges

There is only a certain range to adjust these parameters.
The distance of the panel to the fixation point is constraint by the outer envelope of the satellite with stored panels and the size of the core satellite.
The position of the panel across the fixation point is actually a free parameter unless the panels reach a size that is constrained by the satellites outer envelope.
The length of the hinges is constraint by a minimum length to accommodate all bends into the hinge length and the distance between the fixation points. A maximum length is given by the required stiffness of the panels in the deployed state.
The minimum length of the hinges is quite sensitive to the relative position of the bearing points. In an early mockup setup to test the foldability a configuration was tested where the panel plane ends at the height of the lower hinge bearing (marked with a line in Figure 6). It shows good folding and deployment behavior.

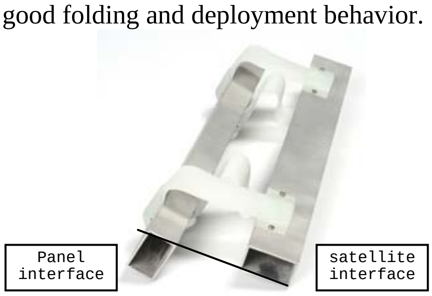


Figure 6. tape spring hinges interface mock-up. Panel edge in line with lower interface mockup

In the actual satellite accommodation the edge of the panel is in line with the upper hinge bearing. The lower hinge connection to the satellite is behind the panel. This configuration is incompatible to the original hinge length. The curvature is put under tension thus reducing the bending radius and overstressing the tapes. Compared to the mock-up the hinge length has to be increased.

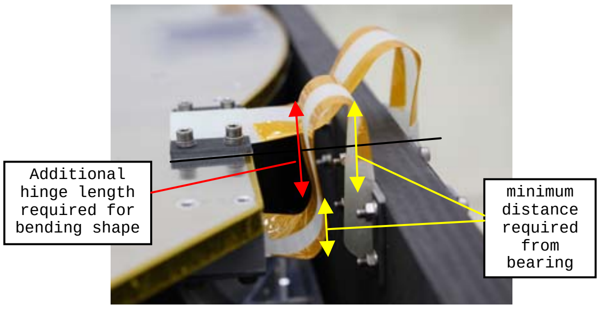


Figure 7. tape spring hinges interface with panel in line with the upper hinge bearing.

The overlap of the Panels with the interface also increases the difficulty in connecting the hinges to the satellite. Part of the installation of the lower hinges has to be done behind the panel, making it quite difficult.
There are two fundamentally different ways to install deployable panels at the tape spring hinges.

- The panel is being installed at the hinges in the deployed state. After integration and fixation of the hinges the hinges are folded and the panels moved to the stored configuration. Then the panels are fixed at the release mechanisms.

Figure 8. Installation of panels in the deployed state followed by folding of the panels.

- The panels are fixed at the release mechanisms in the stowed position. Than the hinges are installed directly in the folded position.

Both methods have significant advantages and disadvantages. Like conventional hinges where the axis should be aligned, the tape spring hinges need to be fixed to be aligned in the deployed state. Otherwise one or more hinges might not snap into the curved profile.
Adjusting the hinges to the panel in the deployed state ensures the position of the hinges when the panel deploys. If the hinges are installed in the folded state it is more difficult to ensure the precise position of the hinges. With thin glass fiber hinges it is not possible to ensure the correct position of the hinges if upper and lower hinge are connected separately.
The folding of the panel from the deployed state after installing the hinges to the stored position is a tricky process. The hinges when folded are not designed to

support a panel under gravity. Therefore an additional MGSE is needed to support the panel during the storing process.
The method chosen is the second one. To ensure the accuracy of the installation the hinges are preinstalled at the panel. On the satellite side a bracket is used that connects upper and lower hinge. This bracket is installed with the tape spring hinges straight. It has to be checked that the distance and parallelism to the panel and the bracket on the other side is accurate.

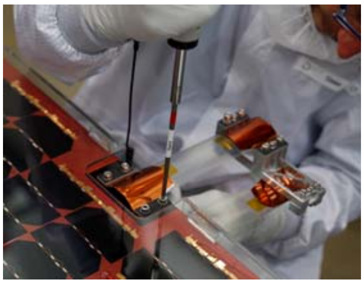


Figure 9. Pre installation of hinges with a bracket on the satellite side.

Once the panel is fixed to the satellite the hinges can be folded and the bracket with both hinges is connected to the satellite.

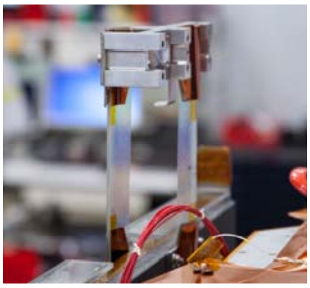


Figure 10. Panel installed at the satellite without the hinges folded.

When folding the hinges it has to be ensured, that the curvature is not pulled towards the ends of the hinge where the profile is stiffened by the interface. This is especially critical on the lower hinge where an additional sheet metal is used to provide a save deformation of the hinge (Figure 11).

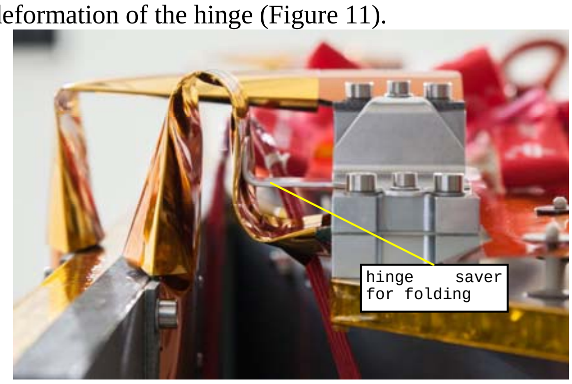


Figure 11. Hinges folded and brackets connected to the satellite. (hinges covered by SLI)

After folding the brackets have to be checked to be at the same distance and parallel as before.

2.4. Deployment trajectory

The tape spring hinges have no dedicated axis to rotate the panel. Right after release the panel moves to a new position where the deformation of the hinges is symmetrical to the position of the fixations. This happens with negligible rotation. After this transversal movement the rotation starts (Note that the two movements are not that clearly separated. But as the lateral forces are higher than the rotational the lateral movement is a lot faster).
A symmetrical configuration between the fixation points of the hinges in the stowed configuration was not feasible by accommodation constraints.
The combination of transversal and rotational movement during the deployment of the panels adds complexity to the system. Predicting the area to be kept free for collision avoidance is more complex and requires additional testing compared to conventional hinges. It also makes the gravity compensation for testing a lot more complex as is describes in chapter 3.

3. TESTS FOR PANEL DEPLOYMENT VERIFICATION

3.1. Verification Strategy

The before described solar panel design has to fulfill satellite accommodation constraints, has to be flexible to some extent for being able to react to late design requirements and moreover implements some innovative technologies. This design has to be verified to show that it fulfills the needs of its intended use.
In the early design phases the mechanism design process uses mainly verification by analysis. These analyses are made for the calculation of pretension in the panel to the standoffs and also analyses for preload (load under vibration) are carried out as input for selection of frangibolt activator [6]. In later processing of the project tests are executed in order to verify the functionality of the solar panel mechanism.
The deployment of the four solar panels is critical for the mission success. On the one hand the generation of power from the solar panel cells is dependent from the panel field of view and thus from the successful deployment. On the other hand the configuration of the panels has an impact on the operability of the spin stabilized satellites´ AOCS function for attitude orientation.
The tests for panel deployment verification are divided into development, qualification and end-to-end/acceptance tests. The development tests are carried out in early project phases. They are used to analyze the performance in order to gain experience with physical influences and involved mechanical interfaces. A broader range of operating conditions - compared to the mechanism specifications - is tested. The development tests are not executed on flight model hardware. Later qualification tests with numerous deployment executions bring confidence to the chosen design. Qualification testing in form of environmental testing

(mechanical vibration & shock plus thermal vacuum) demonstrates that the designed mechanism meets the requirements also with qualification margins. These tests are carried out with structural models representative to flight models.
The used frangibolt activator [1] is a space qualified part with space heritage. The function of this component within the mechanism chain can therefore be assumed as functioning and reliable. This single functional part of the chain is no point of discussion that needs to be respected for the verification planning. But, nonetheless, the influence of the surrounding hardware and its interfaces consisting of several small layers has to be verified by test to assure reliable connection/form closure.
The solar panel deployment mechanism system consists of several self-standing mechanisms (i.e. Frangibolt activators, hinges, locking and interfaces) which all have to function individually for a successful panel deployment. Those single functionalities are somehow independent from each other as they have to function each after each. All of the single mechanism components are based on different principles where different phenomena can occur. Hence, it was defined to test some mechanism principles/basic functions first independently in development tests. The test breakdown was defined to reduce test effort but also to get less complex test data. The following summary shows a list of tests each to prove different concepts of the mechanism chain:

- Structural integrity test of mechanism (shock, vibration).
- Deployment of hinges, arms and panel without frangibolt actuation.
- Thermal influence on the release by the frangibolt fastener.
- Release of a panel by Frangibolts in cleanroom environment as verification of the panel separation functionality with complete mechanism chain and surrounding hardware. Three deployments of a non-flight panel (each two bolt separations) are performed.
- Three deployments of non-flight panels to verify the undisturbed deployment as verification of the deployment functionality with tape spring hinges, stiffener arms and representative surrounding hardware. It shall be shown that the panel does not get stuck during deployment, that the hinges provide a deploying force and that the hinges lock the panels after deployment. The deployment test is also used to demonstrate the correct installation of the hinges by the chosen installation process.
- Vibration test of frangibolt and panel coupon (structural parts of panel around bolt, e.g. stiffening box and skin) to verify separation after vibration and the form closure in bolt fixation. One bolt separation is executed after the vibration test in a clean room environment.
- Measurement of distinct activator characteristics. The frangibolt actuators are activated in thermal vacuum conditions and several properties are measured (compressed length, length after activation, temperature before activation, temperature at activation, activation time).
- Bolt separation test of each flight panel at its dedicated side on the satellite to ensure the accuracy of the interface.
- End-to-end test with satellite on-board computer plus operative system commanding the release of the panel deployment. That means using simulated ground stations via RF link, sending and receiving commands of the satellite on-board-computer and testing the telemetry on downlink side. This is done with one panel (Flight Model) installed and deployed. On the remaining three sides the release mechanisms are operated without a panel. The end-to-end test can actually not be seen as an acceptance test where no later changes are followed as the mechanisms need to be reset and fasteners need to be replaced. But this final tests show that all non-refurbished hardware is in as-designed configuration and also that the flight command chain and harnessing works as intended. It is indeed a characteristic of many mechanisms that their principle of performance can only be verified but not the verification of the actual flight status performance without being reset with the later need of refurbishment can be shown.

Certain combinations cannot be demonstrated with the test equipment in house. As the most versatile gravitational compensation used is a helium balloon a big space above the satellite as well as an atmosphere is needed.
Therefore the deployment under vacuum and relevant thermal condition cannot be tested. As the tape spring hinges change in properties by the given temperature range is considerably small this is accepted by review of design.
A gravity compensation is needed that shall have minimum impact on the panel behavior. Since the panel deployment is a complex combination of linear and rotational movement an influence of the gravity compensation cannot be completely avoided. Results - positives or negative - shall be treated with engineering judgement of the influence of the gravitational compensation.

3.2. Test Setup

As described above the hinges are not able to provide a given axis during deployment under gravity. Therefore gravity compensation had to be chosen to simulate the 0g environment for deployment.
Tested options were:

- Support by a rope hoisted at the overhead crane
- Support by a rope hoisted at the overhead crane with an additional balanced beam for movement support
- Support by a helium filled high altitude balloon

Further options were investigated such as:

- An air bearing table
- A vertical deployment

Those were discarded as a feasible solution was found.

Very early mockup tests were made with a panning arm balancing the panel. The arm provides a support that pan close to the ideal path of the panel with a negligible influence to the movement. To balance a complete panel of 4.7 kg the setup with arm and balancing weight would have been quite heavy. This, in combination with the setup complexity, had to be avoided to be placed above the hardware under test.
With the first deployment tests on the satellite structural model the gravity compensation was realized by an unsuspended rope hoisted to the spacecraft lifting beam. The Lifting beam served, similar to the counterbalanced panning arm, as eccentric guidance for the panel path. As the inertia of a 70kg lifting beam is quite big, the influence to the panel movement proved to be too high, thus preventing a force free deployment.
As a result of the various pre-tests, the support by a helium filled high altitude balloon proved to be most useful for repeated deployment tests. If filled correctly and attached close to the center of gravity, the panel can – while slower - move as given by the tape spring hinge forces.
For the verification tests, the solar panel is released in horizontal configuration while the complete Satellite is mounted in its MGSE. A catching device prevents the panels from ripping off the tape spring assembly in case of failure (see Figure 12, right).
The panel release is filmed with five cameras. The cameras are synchronized by an acoustic signal, triggered by the control room operators at the moment the release command is send. After activation, the panel is released by the stored energy of the tape spring hinges and the panel support arm. High contrast indicator marks on both panel and panel support arm are used to visualize the relative position of the center of gravity.
The principal test assembly is shown in Figure 12 .
To compensate the panel and panel support arm weight of 4,8kg during the deployment process, a standard 1.6m high altitude helium filled balloon is used.
The balloon is mounted with two connections to the solar array assembly: The primary compensator, consisting of a nylon rope with attached aluminum snap hooks, is used to lift the weight of the solar panel itself, estimated with 4,7 kg. As secondary compensator, a flexible pulley with an integrated linear spring element and a retraction length of 1.5 meters is used to compensate the weight of the panel support arm. The pulley system shall provide enough free rope length to allow the panel support arms movement while applying a constant lifting force to the support arm hinge.

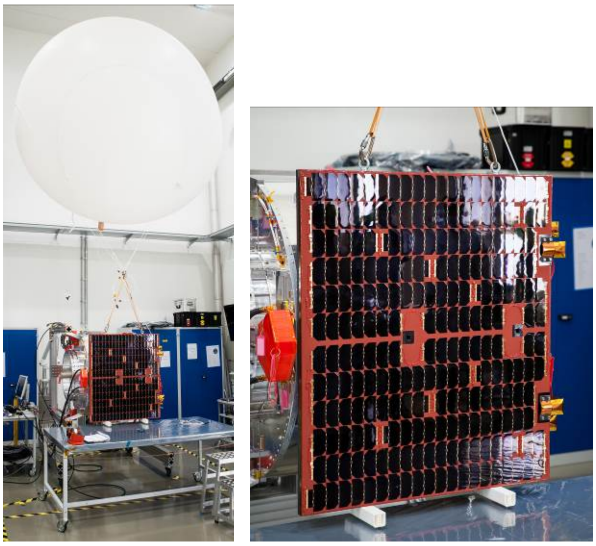
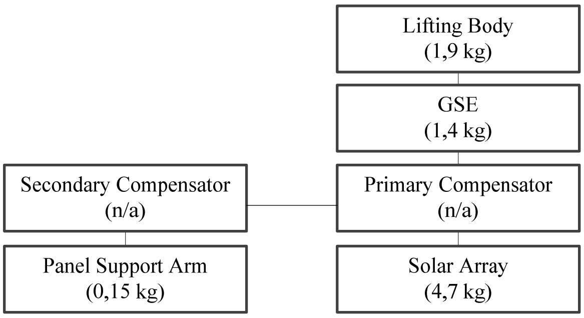


Figure 12. Panel before deployment test. Left: Gravity compensation by helium high altitude balloon. Right: 3D-printed stands and a table secure the panel

The overall weight of the gravity compensation system is estimated with 3,3kg including balloon, compensators, filling and purging equipment and helium. With the payload mass of 4,7kg a total of 6,9kg has to be compensated. This leads to a total needed helium volume of 6,7m³ and a balloon diameter of 2,34m. The lift calibration is done during the filling process using a spring balance.



To estimate the influence, an order-of-magnitude analysis is performed. Two main aspects influence the movement speed of the solar array assembly: The overall weight, impacting the inertia, and the drag force. While the error resulting from the mass gain through the gravity compensation can be directly calculated, the impact of the drag force has to be estimated from the aerodynamic properties of the components. Assuming a rigid connection between panel and gravity compensation, with a perfectly spherical balloon as lifting body, the assumptions as given in Tab. 1 can be made.
As can be seen, the relative drag force, not taking into account movement speed and air density, is nearly doubled by the gravity compensation, while the impact towards the inertia is 68,75%, leading to a total error in force balance and therefore movement speed of at least 189% compared to an uncompensated test setup.

		Panel Assembly	Gravity Compensation assembly	Total
Drag coefficient (cd) by geometry	--	2	0,45	
Area (A)	m²	0,8	4,29	
Rel. Drag (cd · A)	m²	1,6	1,93	3,53
Mass (m)	kg	4,8	3,3	8,1

Table 1 Drag estimation of balloon and panel

4. TEST RESULTS AND ACCORDING ADJUSTMENTS

As explained by Tab. 1. the deployment speed is very low due to the high aerodynamic drag. Also, due to the flexible connection between panel and compensation and the overall flexibility of the rubber balloon hull, the in-plane speed is overlaid by a low frequency, decreasing sinusoidal harmonic wave additionally distorting the overall movement characteristics.
Fig. 13 shows the relative movement speed (v/v_{max}) and angular position (A/A_{max}) of both solar panel ($_{SP}$) and panel support arm ($_{PSA}$).
Fig. 14 shows the deployment seen from below toward the balloon.

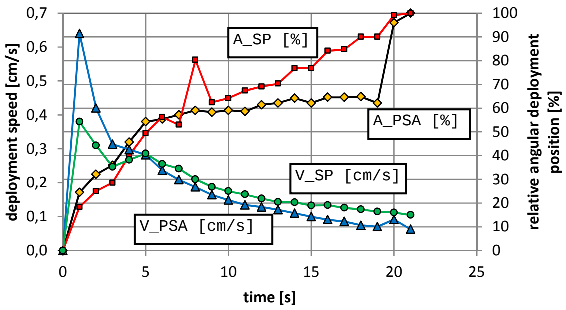


Figure 13. Speed v and angular position A of panel support arm (PSA) and panel (SP)

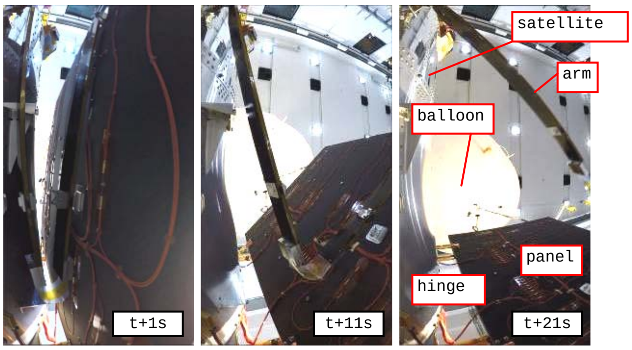


Figure 14. Deployment seen from below

Further observations regarding the feasibility of the test setup were made.
Forces on the test setup need to be compensated quite accurately. The force by the bended hinges is very low and does compensate only for small inaccuracies. Force adjusted gravity compensation like the balloon is superior to one with a fixed height like a rope. The balloon can compensate for tolerances. An oscillation in the direction of the compensation would even be prevented by a fixed rope. Besides those advantages the test lifting force of the helium balloon has to be adjusted accurately. Otherwise the panel can move in the direction of the hinge axis and perform strong oscillations. If the lifting force is too inaccurate the hinges do not snap into the deployed position or the hinges might even take damage. Accurate results regarding the deployment speed in vacuum cannot be measured. For handling in a cleanroom the balloon has to be thoroughly cleaned with compressed air before the use in a clean room and has to be treated very carefully. Both sides of the rubber balloon hull are treated with talcum powder which can contaminate the clean room environment. Constant leakage due to degradation of the cleaned hull limits the lifetime to only a few days.
But besides these considerations the helium balloon proved to be a very flexible tool to demonstrate gravity compensated effects under most degrees of freedom.
The tape spring hinges are a sensitive structure that requires some consideration. While very flexible it has to be ensured to not overstress the hinges locally. The installation has to be very precise to ensure the snap into the undeformed profile. But when handled correctly the hinges provide great advantages. They are most light weight and free of play. No locking force needs to be considered. Therefore the deployment can be slow thus reducing the shock when reaching the deployed position.

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