ARTICULATED DEPLOYMENT SYSTEM FOR ANTENNA REFLECTORS

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ABSTRACT

An articulated deployment system is developed for the deployment and pointing of antenna reflectors with a larger diameter and extended focal length. The articulated boom can be folded in several configurations to stow on the spacecraft sidewall. The boom, made of carbon fibre that is configured for a low CTE of better than ±0.3µm/m-K, deploys by means of spring-driven hinges interconnected via synchronisation cables and is controlled by an actuator. When fully deployed the hinges are latched, providing a stiff structure essential for disturbance-free pointing of the antenna. For pointing, the existing ADTM Mk2 gimbal by Airbus Defence and Space UK is used. The arm is mounted (repeatably) to the spacecraft with an adjustable range of ±7mm in all axes for coarse adjustment and mounted (repeatably) to the reflector with fine adjustment range of ±2mm and ±1.5°.

The reflector boom has a modular design, which allows a wide range of mission configurations by tuning only a few design parameters such as limb length, deployment angles, and the number of articulations required to stow the boom.

1. INTRODUCTION

Airbus Defence and Space Netherlands (formerly Dutch Space) is developing a new product line of articulated deployment systems in response to market needs in satellite telecommunications. The product line of articulated deployment systems primarily comprises deployment booms for ion thruster modules and for antenna reflectors but may be also implemented for other applications. These two primary applications have very different requirements, however, in the design a lot of commonality can be achieved.

This paper focusses on the deployable reflector boom, see Fig. 1. The applications and key requirements are discussed. Furthermore, a trade-off is presented between a boom based on single rotation hinges and a boom using rotary actuators. Finally, the design and performance are presented.

Currently, the unit Engineering Model (EM) test phase has been completed and the construction of an EM of the complete reflector boom is in progress.

2. APPLICATIONS

The typical payload of telecommunication satellites comprises multiple uplink and downlink antennas. The most commonly used antennas are parabolic reflector antennas where the Radio Frequency (RF) signal is transmitted or received by a feedhorn fixed to the spacecraft structure. The feedhorn is located in the focal point of a parabolic reflector resulting in a uniform and focussed beam with a very high directivity and gain.

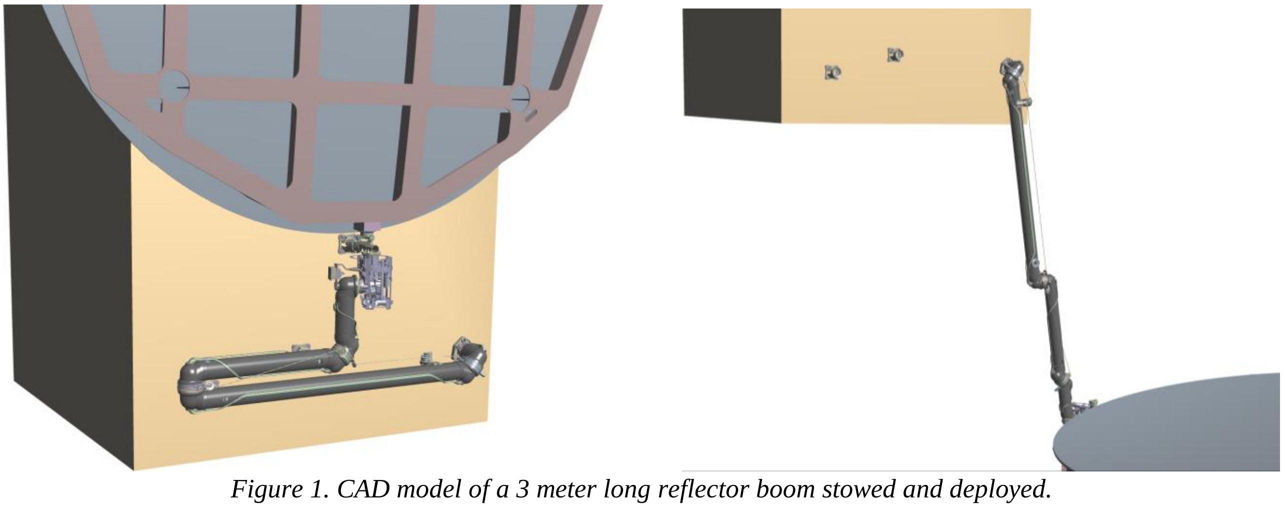

Figure 1. CAD model of a 3 meter long reflector boom stowed and deployed.

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Smaller antennas (short focal length, small reflector aperture) can be accommodated on the Nadir (Earth pointing) side of the spacecraft. Larger antennas have deployable reflectors and are accommodated at the East and West oriented sides. Usually, two reflector structures can be accommodated at each side wall. In the launch phase and transfer orbit, the reflectors are stowed on top of each other. The reflectors are deployed after the final position in geostationary orbit has been reached.

Recent trends in satellite telecommunications demand novel antenna configurations. High-speed internet services and mobile devices call for wider bandwidths and higher antenna gains. This can be achieved by larger reflector apertures and/or longer focal length. Conventional deployable reflectors have a diameter of up to 2.8 m and are attached with a fixed structure to a gimbal at the spacecraft sidewall. The gimbal is a two-axis actuator that performs the deployment of the reflector and maintains the reflector pointing during operational life. The reflector aperture (diameter) is constrained on one hand by the launcher fairing in relation to the spacecraft size and on the other hand by the deployed configuration. Large reflectors must deploy sufficiently far from the spacecraft in order to have sufficient clearance between both reflectors. The focal length is constrained mainly by the spacecraft dimensions. The distance between feedhorn and reflector can be increased by a gregorian configuration (i.e., by illuminating the reflector via a small secondary reflector) or by attaching the reflector onto a deployable articulated boom.

Furthermore, there is a tendency to reduce the platform size, especially in combination with full electric propulsion since this allows the propellant tanks to be reduced in size leading to a further reduction of the platform size. In order to accommodate the same antenna sizes on a smaller platform, deployment booms may be required.

Other applications for deployment booms are e.g.,

- unfurlable reflectors (with diameters exceeding 10 m);
- deployment of a third (or fourth) reflector at the same side;
- innovative stowage concepts (e.g., see Fig. 3d).

3. KEY REQUIREMENTS

3.1. Technical requirements

The key performance requirements are listed in Table 1. In addition to these performance requirements, a number of commercial requirements apply.

Table 1. Key performance requirements

property	***value***	***remark***
thermal distortion	<0.02°	half-cone angle
deployed stiffness	>0.7 Hz	including reflector inertia
mass	<23 kg	for 1.8 m boom length
deployed load capability	>7 Nm	excluding safety factor of 3
pointing step size	0.0025°	

3.2. Modularity

Each antenna has a different configuration. The antenna configuration depends on many parameters. The operator specifies the RF characteristics such as frequency band, band width, coverage area, etc. which result in a mission specific antenna design. The next step is to accommodate the antenna on the platform, particularly the stowed and deployed configurations of the reflectors and the interferences between the adjacent antennae hosted on the platform.

As a consequence the deployment boom concept shall allow the following variability:

- Length from root to tip between ~1.5 m to ~4 m.
- Orientation of boom with respect to spacecraft around S/C *y*- and *z*- axes.
- Pointing direction of deployed reflector around S/C *x*- and *y*- axes (the symmetry axis of the paraboloid is Nadir pointing, however, the reflector is located off-axis, the centre of the paraboloid being outside the reflector surface).
- Stowed position of reflector interface both in-plane (due to variable reflector dimensions) and out-of-plane (due to stacking of reflectors against sidewall).
- Stowed envelope and stay-in zones for the root interface and hold-down points are platform specific.

This variability requires a modular boom design which is customisable to any mission configuration with minimum engineering and qualification effort. This is achieved by a design based on modular, pre-qualified building blocks and the development of models and software tools for automated generation of a mission specific boom design from the stowed and deployed geometry requirements.

3.3. Recurring costs

In the highly competitive satellite communications market, low recurring costs of the equipment is crucial. In addition, a reflector on a deployable boom must be competitive with other antenna configurations such as the gregorian antenna.

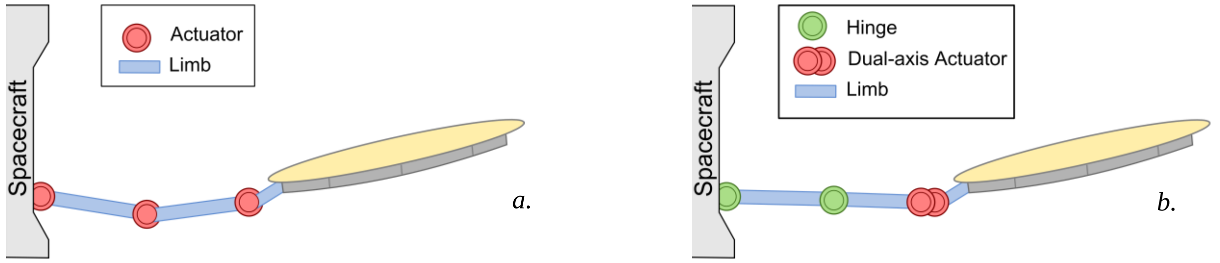

Figure 2. Reflector boom concepts with rotary actuators at the joints (a.) and single rotation hinges (b.). (Rotation axes not shown.)

4. BOOM CONCEPTS

A reflector boom serves primarily two functions:

- to deploy the reflector at a defined distance from the spacecraft
- to perform pointing operations around two axis (roll and pitch) throughout the operational life.

Two different concepts have been evaluated for the articulation of the reflector boom:

a. boom with rotary actuators at the joints
b. boom with single rotation hinges for deployment and a gimbal for pointing

Actuators at joints
Fig. 2.a shows a schematic representation of a reflector boom with actuated joints. The actuators are used both for deployment and for pointing. Therefore, two of the actuators must have orthogonal axes when deployed in order to perform the pointing operations independently. As a result, at least three actuators and limbs are required and for some configurations, a fourth actuator is needed.

The advantage of using rotary actuators is that each limb can be individually actuated in the correct direction. This design is most versatile and can be adapted most easily to a specific antenna configuration. However, rotary actuators with the required step size, backlash, and stiffness are heavy and expensive compared to single rotation hinges.

Single rotation hinges
Another evaluated concept uses single rotation hinges, see Fig. 2.b. The hinges are used for single-shot deployment. In the fully opened position the hinge is latched against an end stop in order to provide sufficient stiffness and to avoid back-driving.

The hinges are synchronized using synchronization cables which are controlled by means of a separate actuator or damper.

For pointing, a dedicated dual-axis actuator (gimbal) is needed. Ideally, the gimbal is located as close as possible to the reflector with both pointing axes (roll and pitch) in the reflector plane. In that case, a pointing operation results in a rotation around the true roll and pitch axes, respectively, without any induced translation. Therefore, the gimbal is located at the tip of the boom and not at the spacecraft side like in conventional deployment structures.

Despite the additional gimbal needed in the hinged solution, this concept is favourable in terms of mass and cost. Furthermore, single rotation hinges can be designed much stiffer and less susceptible for thermal distortion than rotary actuators thanks to the end stops.

The hinged solution has less actuated degrees of freedom to obtain the required configuration, however, it is just as versatile as a boom based on rotary actuators. The half-cone angles and opening angles of the hinges are pre-set to obtain any deployed position and orientation from a given stowed position of the reflector.

5. BOOM CONFIGURATIONS

A wide variety of stowed configurations can be obtained from a set of predefined building blocks. Some examples of stowed configurations are shown in Fig. 3.

The deployed configuration is determined solely by the antenna design and is independent of the stowed configuration as long as the stowed envelope is sufficient to accommodate the required boom length. The primary deployment is done by means of synchronized hinges. After primary deployment the reflector boom is fully extended. In the secondary deployment stage, the reflector is rotated into the correct orientation using the roll and pitch actuators of the gimbal at the tip of the boom. A typical deployment trajectory is illustrated in Fig. 4. Since the hinge rotations are synchronised, there is no variation in the deployment trajectory, thus simplifying the deployment sequence. The risk of colliding with an already

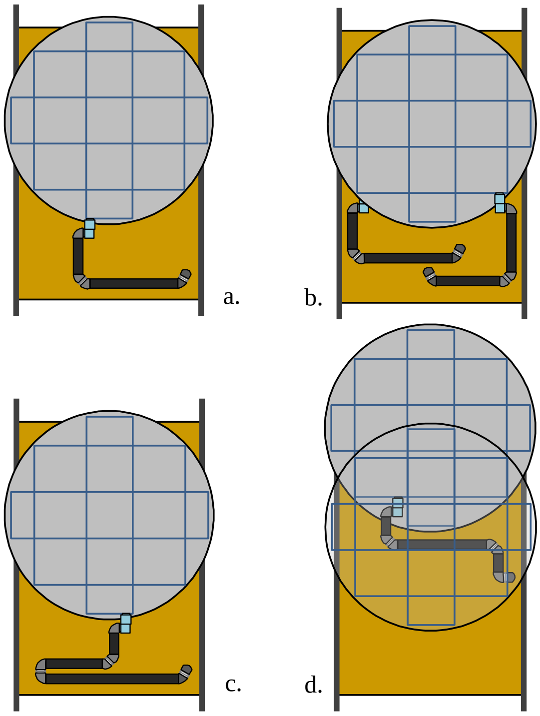

Figure 3. Some examples of stowed configurations (gimbal shown in blue):
a.) standard two-hinge variant;
b.) two stacked reflectors with two-hinge variants;
c.) three hinge variant;
d.) three-hinge variant stowed behind another reflector.

deployed reflector is negligible because the trajectory is dictated by a kinematic motion, which is analysed upfront with a kinematic modelling tool and verified in CAD.

6. DESIGN

Fig. 1 presents a CAD model of a reflector boom with three hinges. Other variants, such as the variants shown in Fig. 3, can be constructed from the same building blocks. This section describes the design of these building blocks in more detail.

6.1. Single rotation hinges

The single rotation hinges (see. Fig. 5) consist of a bearing unit, a drive unit, and two CFRP hinge brackets for minimal thermo-elastic distortion. In the bearing unit a superduplex angular contact bearing from ADR-Alcen has been used. The operational temperature range allows the use of Fomblin Z25 wet lubrication without the need for heaters. The duplex bearing has been designed for maximum angular stiffness (>200,000 Nm/rad) while the bearing friction is negligible. The bearing is axially clamped with a force

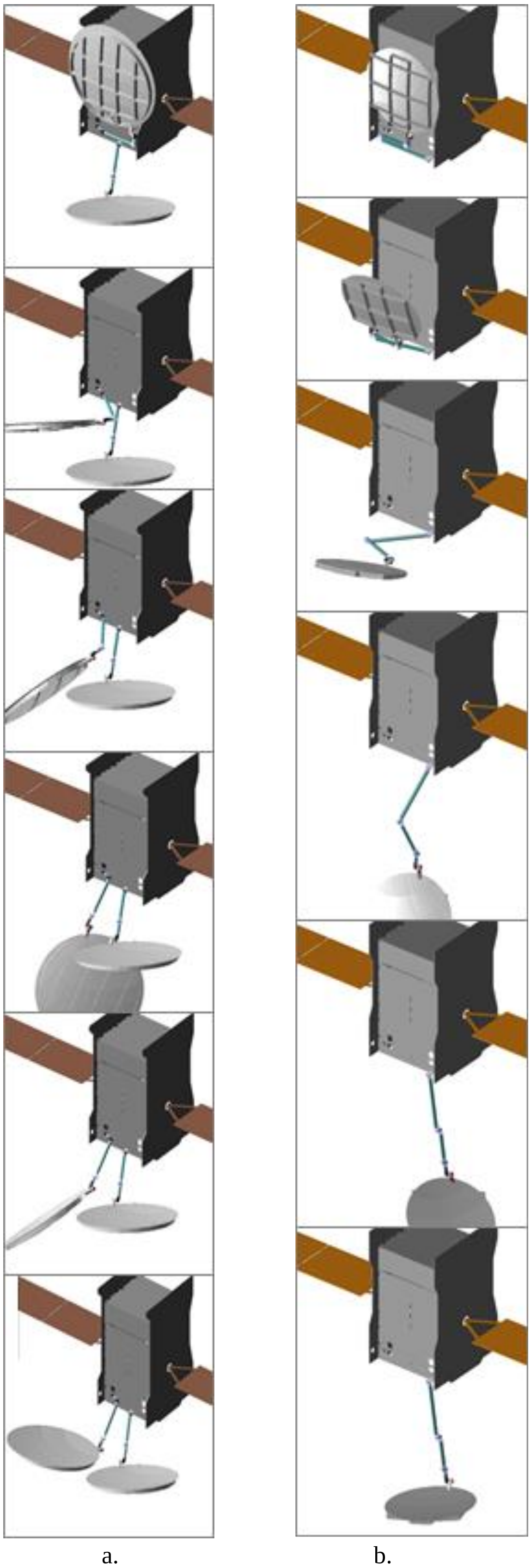

Figure 4. Deployment trajectories of two reflector boom variants: a.) two-hinge variant; b.) three-hinge variant.

Figure 5. Single rotation hinge mechanism (EM).

of more than 10 times the internal preload using dedicated clamping nuts. All parts in the bearing unit are made of stainless steel 440C in order to prevent any loss of preload due to temperature variations.

The hinge is equipped with a hard end-stop. When the end-stop is reached, a lever arm is engaged to prevent back-driving and to increase the contact stiffness of the end stop. The pointing performance is maintained for spacecraft accelerations typical for station keeping. Higher loads of up to 50 Nm can be applied without back-driving but some depointing will occur.

The hinge is motorised by a set of constant torque springs. Each spring delivers a torque of 0.65 Nm and the number of springs can be varied to tune the required torque. Three or four springs are needed to obtain a motorisation margin in accordance to ECSS-E-ST-33-01C whereas up to eight springs could be accommodated in case a higher torque is needed.

The hinge has an open shaft through which the cable harness for the gimbal is routed.

6.2. CFRP tubes

The limbs in between the hinges are filament wound CFRP tubes with an inner diameter of 100 mm (see Fig. 6). The fibre lay-up is designed for minimum thermal expansion coefficient (CTE) in the range of ±0.3 µm/m-K. The actual CTE has been tested using Michelson interferometry. After stabilisation of the CFRP matrix, which occurs within 10 thermal cycles, the CTE varies with temperature between -0.2 and +0.2 µm/m-K in the operational temperature range.

The stiffness is another important design parameter, however, with the current design the boom stiffness is dominated by the mechanisms (hinges and gimbal) rather than by the CFRP tubes for boom lengths of up to

Figure 6. CFRP Tube in four-point bending test set-up.

~4 m. If needed for a certain application, the tube stiffness can be increased by optimising the fibre lay-up for stiffness at the expense of a slightly increased CTE.

Since the CFRP tubes and hinge brackets have approximately matching CTE values, they can be bonded with an adhesive with minimal thermal stress in the bond line.

6.3. Gimbal

The gimbal is an off-the-shelf Advanced Deployment & Trimming Mechanism Mark2 (ADTM-Mk2) by Airbus Defence and Space UK (see Fig. 7). Currently, more than 23 units are in orbit with an accumulated life of over 80 years. The ADTM Mk2 is described in [1].

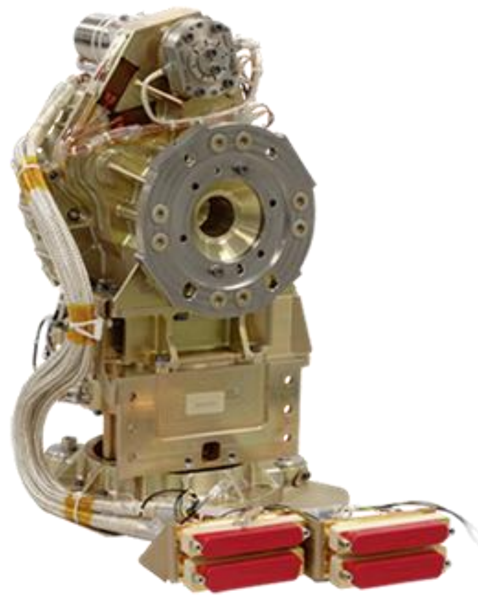

Figure 7. ADTM-Mk2 Gimbal.
(picture Airbus Defence and Space UK)

6.4. Deployment system

All hinges are spring motorised. To avoid uncontrolled deployment and release of spring energy into the system, a deployment system is used which is derived from to the synchronisation system of solar arrays. The hinges are equipped with a cable pulley which also acts as a thermal shield for the hinge. From the pulleys, pre-tensioned Kevlar cables are routed to a pulley on a rotary actuator. This actuator is designed to deliver a high unpowered holding torque and pull-out torque by means of a built-in magnetic detent brake.
After release of the hold-downs, the reflector boom remains stowed against the hold-down brackets since the motorisation torque from the hinges is restrained by the pre-tensioned synchronization cables. When the actuator is driven, the Kevlar cable is unwound from the actuator pulley and the hinges are opened in a synchronised manner until the end stops are reached and the hinges latch.

The dynamic behaviour of the deployment system is analysed in a multi-body dynamics simulation in MSC/Adams. Fig. 8 shows a screenshot of the analysis. The analysis includes the dynamic behaviour of the boom and reflector upon release of the hold-down mechanisms and the loads on all critical components (including inertial loads) throughout the all deployment stages. An engineering model has been built to test the deployment dynamics with representative inertial loads.

6.5. Hold-down and Release Mechanism

The reflector boom has one hold-down point per limb and one hold-down point at the reflector interface. The latter hold-down ensures that the launch loads are not transferred via the reflector.

The hold-downs are attached to the CFRP tubes in the vicinity of the hinges, where the mass concentration is high. The release actuator is a Non-Explosive Low Shock (NELS) device described in [2] (see Fig. 9). It is an evolution of the hold-down and release systems used by Airbus Defence and Space NL for solar arrays with >500 successful releases in orbit without failure. The NELS is based on the principle of cutting a high-strength fibre-based restraint cable with a thermal knife.

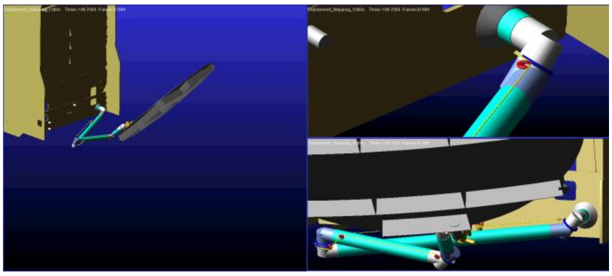

Figure 8. Screenshot of multi-body dynamic analysis in MSC/Adams.

Figure 9. NELS Hold-down and release mechanism adapted for the reflector boom.

For the reflector boom, the NELS actuator is mounted in an adapted hold-down bracket with extended adjustment range (±8 mm) in all directions to allow for tolerance stack-up at spacecraft integration. The release plane consists of a spherical element of carbon-filled PEEK at boom side and a conical element of titanium at spacecraft side. The spherical element is able to rotate in the conical element (±2°) in all three directions to accommodate any misalignment at integration. The assembly is preloaded at 15,000 N by the restraint cable. This preload is transferred to the CFRP tube via an insert inside the tube such that the tube wall is loaded without pressing the tube into an oval shape.

6.6. Adjustable mounts

At both ends of the boom (i.e., at spacecraft side and at reflector side) an adjustable, iso-static mount is present. At spacecraft side, the adjustable mount has the following features:

- In-plane adjustment of ±8 mm
- Out-of-plane adjustment of ±4 mm (additional adjustment possible with pre machined shims)
- Angular adjustment of 3°
- Iso-static mount with a reproducibility of 0.002° between successive (dis)mounting operations.

The adjustable mount at the reflector side is similar. However, it has a reduced adjustment range. Coarse alignment of the reflector boom will be done at spacecraft side and fine adjustment at the reflector side. The iso-static mounts allow remounting of the reflector boom without the need to realign the reflector, e.g., for thermal testing of the spacecraft.

7. PERFORMANCE

7.1. Deployed frequency

The deployed frequency is one of the key performance parameters. Currently, the stiffness has been measured on unit level and are fed back into analysis on boom level. The analysed deployed frequency varies from 0.74 Hz for a 3.2 m long boom with three hinges up to >1.0 Hz for a 2 m boom with two hinges. In both cases a reflector of 3.5 m diameter and 40 kg has been used in the analysis. A rigid spacecraft structure is assumed.

7.2. Thermo-elastic distortion

Thermo-elastic distortion is critical for pointing, and therefore, for the antenna gain. Especially when the boom is subjected to large flux variations in a short time, *e.g.*, at entry and exit of a (spacecraft) eclipse, the thermal distortion is difficult to compensate for with the gimbal.

Thermo-elastic distortion is caused by three effects:

- Lateral gradients due to a heat flux from one side resulting in angular displacement.
- Thermal expansion of the boom resulting in a longitudinal displacement of the tip.
- Thermal stresses at interfaces between materials with a CTE mismatch.

All three effects have been taken into account in the boom design. Most of the structure is made of CFRP with a CTE near zero. The main metal parts in the structure are the bearing units of the hinges, and the adjustable interface mounts. The bearing units have been designed as compact as possible. The interfaces with the CFRP brackets are close to each other and symmetrical, minimising the impact of thermal distortion. The gradient inside the bearing unit is minimised by proper shielding of the unit against direct sunlight by the cable pulleys which are thermally insulated from the hinge.

The major elements in the adjustable mounts are made of aluminium. Despite the high CTE of aluminium, the thermal gradient is low (~0.2°C) thanks to the excellent conductivity.

In order to further minimise the thermo-elastic distortion due to lateral gradients, the complete structure is protected with thermal blankets in order to meet the stringent thermo-elastic depointing requirement. Multi-Layer Insulation (MLI) blankets reduce the thermal gradients in the structure and dampen the temperature fluctuations. A worst case thermo-elastic distortion of 0.019° at the reflector interface has been analysed for a three-hinge boom.

Table 2. Mass prediction

Configuration	***nominal***	***incl. contingency***
2 hinges, 1.8 m	22.6 kg	24.3 kg
3 hinges, 3.2 m	28.2 kg	30.5 kg

7.3. Mass

Based on measured weight of the EM units, a mass analysis was done on the entire reflector boom. The mass prediction is provided in Table 2. Note that the presented masses are including hold-down and release mechanisms and gimbal.

8. TEST PLAN

The breadboard phase and unit EM phase have been completed. Unit qualification tests are planned for the single rotation hinge (incl. installed cable harness through the shaft), the hold-down and release mechanism, and the CFRP components.

An EM of the complete reflector boom has been built using flight grade units. This EM will be used for

- Validation of the MGSE
- Deployment testing (functional testing and dynamic characterisation)
- Alignment verification
- Deployment repeatability test
- Stiffness, proofload, and hysteresis tests
- Vibration testing (sine, random, shock)
- Thermal vacuum release & (partial) deployment test

After completion of the system EM test phase (planned for end 2015) a qualification model or proto-flight model will be built.

9. CONCLUSION

An articulated deployment system for antenna reflectors can be used to increase the antenna's focal length and to accommodate larger reflector apertures. A reflector boom based on synchronised single rotation hinges offers the best performance in terms of stiffness, thermo-elastic behaviour, mass and cost compared to a boom with rotary actuators at each of the joints. The boom design is presented and analysed. Unit engineering models have been tested. The construction of an engineering model of the complete reflector boom is in progress and will be followed by EM testing and subsequent qualification.

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10. REFERENCES

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