ABSTRACT

This paper presents the results from ESA technology preparatory program for Gaia Astrometric Mission to develop a deployable sunshield as part of the passive thermal control of the platform. The description of the design process from requirements and concept selection to presentation of verification activities and test results will be the scope of the paper focusing on the mechanisms side.

1. INTRODUCTION

The Gaia sunshield is a 11 m diameter deployable shield composed by twelve identical frames holding the isolator layers arranged around a central body (the service module) which are deployed simultaneously. The frames provide support to two parallel shielding layers separated 130 mm through flexible supports that provides compatibility with deployment, tension when deployed, and flatness of the deployed shield. The deploying mechanisms of the sunshield include synchronization function of the frames, and provision of tensioning of the shielding layers with a specific support.

Fig. 1 Gaia Sunshield just before end of deployment.

The novelty of the mechanism resides in the requirements of deployed shape (flatness) and the thermal isolator layers arrangement when deployed to meet thermal requirements. This leads to a new method of deploying large thermal isolator surfaces as well as providing new methods of providing flatness in large surfaces.

Fig. 2 Gaia Sunshield Development Model in deployed position during integration.

All frames are spring loaded to provide motorization and the deployment is controlled by one low melting allow regulator [1]. Each frame has its own hold down and release mechanism and end-stops and latching to provide the required planarity when deployed.

The shielding layers are folded in a particular way to minimize degradation of the optical surfaces, comply with the stowed envelope and be compatible with the deployment. They have been designed to provide an unambiguous deployment from a cylinder shaped configuration to a circular and flat configuration covering a diameter of 11 m when deployed.

A full scale model of two adjacent frames of the sunshield has been manufactured and tested and results are presented. Deployment tests will be shown with the
shield deployment process and measurement of flatness, synchronization and tensioning of shield.

Fig. 3 Gaia sunshield deployed (sunside).

2. DESIGN REQUIREMENTS

The major requirements for the Gaia Deployable Sunshield can be summarised as follows:

2.1 Envelopes and size
- Stowed envelope to fit between internal diameter of 3200 mm (the S/C constraint) and an external diameter of 3760 mm (launcher fairing constraint).
- Provide a shield diameter of 11 m (S/C orientation to the sun and S/C height constraint).

2.2 Thermal stability
- Provide a low (150ºK) and stable (1e-3 ºK) temperature to the Payload module over a S/C rotation period of 6 hours
- Provide thermal stability when thermal perturbations due to sunshield shape or sudden solar constant variation

2.3 Structural stiffness
- Provide lateral natural mode frequency higher than 35 Hz
- Provide axial natural mode frequency higher than 50 Hz

2.4 Interfaces
- Attachment area at the base of the S/C on the rear side of the fixed solar array panels
- Attachment area on the Payload module
- Provide allocation for solar panels (11 m2)

2.5 Mass
- The mass of the complete assembly less than 70 kg.

2.6 Deployment
- Initiated by S/C command
- Position monitorization
- Compliance to ECSS rules

3. SUNSHIELD CONCEPT MAIN TRADE-OFFs

During a previous phase of the activity it was found that there were two requirements that were restraining the concept for the sunshield: The solar array allocation and the shape (planarity) to avoid thermal instabilities. These two requirements limited the feasible concept selection by rejecting the concepts based on inflatable, deployable truss structures or collapsible masts due to the difficulty to implement solar panels (about 11 m2 in total) on them and at the same time provide a good flatness over the 90 m2 surface of the sunshield. Therefore the trade off was focused on the selection of the design solutions for a concept based on the following assumptions:

- Structural concept based on rigid structure supporting the thermal isolator.
- Simultaneous deployment of structural elements and sunshield thermal isolator.
- Construction with repetitive sections arranged around the S/C
- Simultaneous deployment of all sections
- Deployment of the structural element by a rotation around an axis tangential to the S/C body

In addition the thermal analyses showed that the thermal performances would be achieved with two thermal foils arranged parallel each other. The sun side blanket should be as flat as possible and with good parallelism with the S/C horizontal plane. Therefore the number and arrangement of the Sunshield thermal isolator were frozen at the time of the trade off.

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<thead>
<tr>
<th>Structure</th>
<th>Candidate #1</th>
<th>Candidate #2</th>
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<tbody>
<tr>
<td>Actuation System</td>
<td><img src="image1" alt="Actuation System" /></td>
<td><img src="image2" alt="Actuation System" /></td>
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<tr>
<td>Synchronising Mechanism</td>
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<tr>
<td>Shield Thermal Insulator</td>
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<td>STI stowed configuration</td>
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<td>HRDM</td>
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Fig. 4 Trade off matrix.

The main elements subjected to trade off were selected according to their influence to the performance requirements. Fig. 4 shows the alternatives considered that were the following:
The structural concept that affected mainly the mass and frequencies of the structure. (X shaped, square shaped or beam shaped)

- The packing concept of the thermal isolator which affects the thermal performance due to degradation during folding/unfolding process. (high packaging and many folding lines or low packaging and few folding lines)

- The sunshield thermal isolator material as a balance of mass, thermal performances and mechanical properties.

- The deployment synchronization concept between sections. (Bellows, cardan, cable)

- The actuation concept. (spring with regulator, motorized, etc)

- The Hold down and release concept mainly selecting an individual release of sections or a common release point for all sections. (Pyrodevices, memory metal based release of cable cutter release)

4. DESIGN DESCRIPTION

The final baseline coming from the trade off and compatible with the basic concept of repetitive sections arranged around the S/C consist on the following elements:

- A twelve frames arrangement
- X shaped structure frames made of CFRP beams/tubes and fittings
- A spring actuated hinge mechanism, one per frame providing the deployment torque
- A cinematic coupling of all the frames by bellows
- One deployment regulator to control the deployment of the twelve frames based on low melting alloy [1]
- Pyrodevice release or alternatively a memory metal release mechanism to avoid shocks and contamination [2]
- Folding pattern of the thermal blankets with the minimum number of folding lines

The mechanical design was configured as shown in fig.5. The frames are arranged around the S/C central body and are hinged at the base. These frames are tubular structures which supports a CFRP sandwich panel on which the solar cells are bonded. The frames are X shaped and at the crossing point it is located the Hold down and release mechanism that has an interface to the upper part of the S/C. The Sunshield Thermal Isolator (STI), the blankets, are attached to the structure frame and are divided in different parts: One part is not foldable and maintains its shape (squared) and configuration during the whole deployment. A second part is foldable and include in the construction some reduced thickness lines which create folding lines on the blanket.

The deploying mechanism is based on the design of Ref. 1 and all frames are cinematically connected through the hinges by a mechanical coupling based on a bellow.

The attachment of the STI to the structure is performed through some specific devices providing a controlled flexibility in the plane of the STI with an admissible deformation larger than 40 mm. This deformation is required in order to accommodate the shrinkage of the STI due to the temperature excursion from ambient to operational temperature at 150ºK.

The design of these devices have been optimized to provide this controlled flexibility and high deformation capability in a limited volume and to minimize the angular deformation of the STI in the attachment points.

5. ANALYSES OF PERFORMANCES

5.1 Structural and thermal requirements

The structural and thermal requirements were analyzed using Nastran for the optimization of the structural concept and ESARAD for the verification of the thermal performances of the sunshield. The details of these analyses are not needed for the understanding of the mechanisms of the sunshield, however they confirmed the requirement to the mechanism to have a deployment accuracy of better than 0,02º.

This accuracy allocation for the mechanism was determined from the thermal analysis by assessing the maximum permissible deviation of the sunshield to achieve the thermal stability and accounting the deformations of the thermal blanket due to the solar pressure.
5.2 **Analysis of the deployment**

The main requirements for the sunshield deployment are the following:
- Comply with the ECSS mechanism requirements and
- Provide a deployed accuracy of better than 0,04º of all frames

Therefore the analyses of the deployment were focused in the following performances:
- The torque margin analysis including the effect of the synchronization and the torque due to the deployable STI tensioning
- The performances of the synchronization to have positive latching in all frames at the end of the deployment
- The pointing and adjustment capability

5.3 **Torque margin**

The torque analysis showed that the main sources of torque acting during the deployment come from the following sources:
- The actuating spring which provides the positive torque for deployment
- The deployable STI tensioning that starts at around 40º from the start of the deployment as a resistive torque and finishes at the end of the deployment as an actuating torque
- The deployment regulator that in addition to maintain a constant velocity of the deployment provides a small friction
- The hinges friction
- The synchronization mechanism (bellow) friction and hysteresis losses.
- The latch locking at the end of the deployment

The major contributor to these torques apart from the actuating spring is the STI tensioning. During the deployment the STI starts to tension through the flexible attachments to the structure. These attachments provide a tensioning force at each corner of the blanket of about 15 N. This force at each corner is not aligned to the deployment axis and provides, first a resistant torque and at the end of the deployment an actuating torque. This provides an additional margin to the deployment at the end when the spring provides less torque and the locking latches actuates.

5.4 **Synchronization**

The synchronization of the frames is performed at hinge level by specific couplings based on bellows and also by the deployable STI. In the analysis cases as a conservative assumption, only the bellow has been considered as a synchronization element.

The synchronization main objective is to link all frames to the deployment regulator, which controls the deployment speed.

A perfect synchronization mechanism would give the same deployment speed to all frames which should reach the end of the deployment at the same time. However the limited stiffness of the synchronization leads to angular mismatches between frames and therefore not all frames arrive to the end-stop simultaneously.
the capture range of the locking latch in order to guarantee safe locking and that all frames arrive to the end-stop even with a one spring failure.

In fig.7 it is shown the sequence of latching of the different frames arranged radially and the difference of angles between frames at four different stages of the deployment. This analysis only accounts the synchronization effect of the bellows, but the deployable STI provides additional synchronization capability to the adjacent frames.

6. DEVELOPMENT MODEL DESCRIPTION

6.1 Scaled mock-up

The pattern of the folding lines of the blankets to have a unambiguous and repetitive deployment was studied with the construction of a scaled model of the sunshield. The purpose of this mock-up was to study the packaging of the blankets and the way they fold and unfold and the arrangement of the optimum folding lines pattern on the STI. This mock-up served to demonstrate the feasibility of the folding concept and to prepare the design of the blankets.

Once the STI folding concept was verified the definition of a representative demonstration model in full scale started with this baseline design

6.2 Description of the demonstrator

Due to the budget constraints, a full scale model of the complete sunshield was not feasible. Therefore the construction of a development model should have limitations either in size or in number of elements.

It was decided to have a demonstrator model in full scale but with only two frames. This decision was adopted due to the following reasons:

- A full scale design could be better adapted to converge to a flight design.
- Miniaturization of parts would not have the same mechanical properties as a full scale (natural frequencies, torque margin, etc)
- Mechanical components used for the demonstrator could be also used for the flight model
- Identification of integration aspects is only possible with a full scale model
- Quantification of sunshield shape only possible in full scale.
- Thermal vacuum and vibration tests already done at deployment mechanism level
- Shrinkage of thermal blankets can be considered by a shrunk blanket dimensions design

Therefore the definition of the demonstrator was done with the following objectives:

- Prove the deployment aspects:
  - Torque margin
  - Synchronization of frames (limited to only two frames)
  - Folding/unfolding of STI
- Prove the mechanical behaviour, deployment frequency, stowed natural frequency
- Quantify the planarity and repeatability for thermal performances assessment
- Define the integration process at S/C level

The demonstrator was built with two adjacent frames. The STI includes both the two frames in the sun-side and shadow-side and a deployable STI section composed also by the two, sun and shadow, facing layers.

The synchronization include the coupling between the two frames and the adjacent ones, therefore there are three couplings, two in the extremes and one between frames.

Contrarily to the flight configuration, the demonstrator has only one active frame motorized with a torsion spring. This configuration represents the worst case deployment for torque margin. In addition the deployment regulator can be attached either to the active frame or two frames apart. This gives two different
cases of synchronization and latching and permits the assessment of the influence of the performances of the synchronization in the deployment.

7. TEST CAMPAIGN RESULTS

7.1 Component level tests
Prior to the full scale demonstrator integration, a characterization of the key elements of the deployment mechanism was performed: The synchronization coupling and the STI flexible attachment to the structure.

The coupling attaching adjacent frames is based on a metallic bellow that connects two hinges with an angular mismatch of 30°. Couplings, either Cardan joints or bellows, are not efficient with this angular mismatch however bellows offer the best ratio of torque transmission versus mass.

Due to the difficulty to model the behaviour of the bellow, it was decided to submit a bellow to characterization of stiffness and torque loss.

![Fig. 10 Bellow buckling at four times rated torque](image)

The stiffness test showed that the bellow performances are reduced with an angular mismatch of 30°. The local buckling of the bellow was apparent at 20% of the rated torque for a straight bellow and produced permanent deformations. However the bellow provides coupling capability with a reduced stiffness for five times the rated torque and did not show further degradation apart from the permanent deformation.

The coupling was also submitted to a test to quantify the torque losses that can be expected due to the torque transmission with a 30° angular mismatch between ends.

It was found that the loss was about 5% the transmitted torque up to half the rated torque. From that point the twisting of the bellow due to the local buckling produce the contacts between corrugations and the significant increase of losses.

![Fig. 11 Torque loss on bellow](image)

The attachment of the STI to the structure of the sunshield is the second element of the sunshield that affects the deployment. The flexible element was tested to define the influence in the torque budget.

The STI attachment to the flexible element is performed by riveting. This is a non conventional method of attaching blankets to a structure and was designed to allow significant force transfer without relying on adhesives that are susceptible to creep. The tension of the STI should be maintained during the sunshield lifetime to guarantee the planarity required and therefore it is important to avoid creep and have wide margin in the attachment.

Three samples of each material type (sun-side and shadow-side materials) was submitted to tension load up to rupture.

![Fig. 12 STI destructive test samples. Teflon 5mil (left) and Kapton™ 1mil (right)](image)

Two materials was tested, Teflon (FEP) 5mil and Kapton™ 1 mil.

The Teflon shows a high creep before failure and a reduction of thickness when subjected to tension. This is not good for a riveted joint in which part of the load is transferred by friction due to the clamping force between the Teflon and the metallic parts. Once this friction force is not enough to transmit the tension, the Teflon is working against the rivet and yields.
Table 1 Failure loads of the STI attachment with different materials

The riveting joint with Kapton™ does not show a thickness reduction due to tension and the joint works perfectly. The failure occurred in all cases by tension, with no significant yield in the minimum section area.

The STI attachment was also tested as bonding path to the STI with a bonding resistance of 300 mΩ.

7.2 Sunshield level tests

The sunshield demonstrator tests were divided in different performance measurements:

- The torque margin was assessed by the measurement of torque at the level of the hinge in different conditions. It was found that the zero-g off loading device contributed significantly to the overall torque budget.
- The positive latching and synchronization was verified in all deployments. It was found that the synchronization is performed only by the bellow during the whole deployment and at the end of the deployment the deployable STI synchronizes the adjacent frames reducing the angular difference between frames at the end of the deployment. This can be seen in Fig. 13 and 14.
- The deployable STI provide a significant actuating torque at the end of the deployment. This effect improve the synchronization between frames and guarantees a complete deployment even in case no torque is provided at hinge level by a spring.
- The planarity measurement showed that the repeatability of the deployment is in the range of 0.03° and the maximum deviation of the sun-side blanket to a plane surface is around 5 mm for a 4 x 4 m² surface and is mainly produced by the waving of the hanging blanket.

The deployment of the sunshield was verified in two worst case configurations. In the first one the deployment regulator (DR) driving the deployment was installed in the active frame and therefore the positive torque of the spring was held by the regulator directly with no intermediate flexibilities. This deployment case showed that there is still some flexibility acting between the spring and the deployment regulator that produces an initial angular displacement of 10° at the release of the frames. This angular excursion is due to the flexibility of the deployment regulator output that has not been optimized for this application. Once the deployment regulator is activated and after a heating period, the low melting alloy of the regulator begin to yield and the deployment starts.

![Deployment curve. DR in active hinge.](image)

![Deployment curve. DR in passive hinge.](image)

During the first degrees of deployment the angular mismatch between frames is due to the bellow stiffness and the transmitted torque that is the resistant torque from the passive frame. At the end of the deployment the deployable STI joining the two adjacent frames synchronizes the deployment and the angular mismatch disappears.

The test is repeated in a second configuration in which the deployment regulator holding the frames is attached to the extreme of the passive panel while the spring is actuating the active panel. The angular mismatch between frames in this case is maximum because the active frame is directly driven by the spring providing the maximum possible torque and therefore deforming the bellow to the maximum. This angular mismatch is maintained during most of the deployment and only at the very end of the deployment the deployable STI is
able to reduce this angular difference between the two frames. This case verifies that the deployment of one frame can occur even with the failure of one spring and even in this case the latching will be positive. The deployment synchronization can be performed by the bellows coupling because angular differences between frames do not affect the deployment performances. Only at the end of the deployment the deployable STI actuates to provide the synchronization and positive deployment torque to the frame with no spring to achieve the full deployment.

8. LESSONS LEARNT
One important source of problems during the test campaign was the performance of the zero-g kit to off-load the frames and compensate all gravity torques at hinge level. These problems were increased with the size of the mechanism and the available envelope in the facility.

The design of the zero-g kit of mechanisms of the size of the sunshield requires special attention which was not anticipated to the appropriate level in the development plan.

9. CONCLUSIONS
The Gaia sunshield has proven a robust design to provide a reliable deployment complying with the performances required for the mission. This has been achieved with the use of space rated products that simplifies the control of the deployment.

The main requirements of the sunshield related to mechanisms have been verified: Thermal performances by a combination of analysis and tests (planarity), interfaces and deployment.

The deployment of all frames at the same time has been proven to be reliable with the present design due to the redundancy of the actuating elements (one spring per frame) and the positive torque provided by the deployable thermal blanket at the end of the deployment.

10. ACKNOWLEDGEMENT
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11. REFERENCES
1. “Regulated deployment mechanism for a panel like appendage”, 9th European Space Mechanisms & Tribology Symposium, Liège, Belgium, Proceedings ESA SP-480, September 2001