Development of New Type of Flexible Solar Array for Constellations up to 5 Kw

In the frame of ESA Contract No. C4000137422/22/NL/FE

“ESR – Executive Summary Report”

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1. INTRODUCTION, PURPOSE AND SCOPE OF THE REPORT

1.1 INTRODUCTION

This document is the Executive Summary Report (ESR), delivered according to the AD01 contract and AD02 SoW.. The Executive Summary Report is an opportunity to share the significant features of the TDE activity. This document presents an introduction, objectives, findings, recommendations, and a conclusion.

1.2 PURPOSE AND SCOPE OF THE REPORT

The main purpose of this report is to outline the project's objectives, findings, recommendations, and a conclusion. The project report includes 4 sections providing details about:

- the project's goals (Section 2): in this section the background related to high performance flexible solar arrays is presented, including the description of Thales Alenia Space perspective. This section also defines and clarifies the objective of the activity in the form of a statement.
- the project progressing (Section 3): in this section the methodology and way of progress on a project are described, taking into account crucial findings.
- the project conclusions (Section 4): In this section the changes and effects taken place after implementing the project are presented. The conclusions are presented in terms of positive accomplishment already tangible for the space community and in terms of strategy for further developments.

1.3 APPLICABLE DOCUMENTS

AD Ref.	Document Designation	Document Reference	Issue	Date
AD01	ESA Contract	No. C4000137422 /22/NL/FE	1	01/03/2022
AD02	DEVELOPMENT OF NEW TYPE OF FLEXIBLE SOLAR ARRAY FOR CONSTELLATIONS UP TO 5 KW	ESA-TEC-TDE-SOW-023339	1	10/06/2021
AD03	New Type of Flexible Solar Array for Constellations up to 5KW	TAS-21/CI-DCE-286	1	07/09/2021

1.4 REFERENCE DOCUMENTS

RD Ref.	Document Designation	Document Reference	Issue
RD01	TN1- Deployment Scheme Summary	0005-0015797095	01
RD02	TN2 - Preliminary Design Description	0005-0017470580	01
RD03	TN3 – Mechanical Analyses	0005-0016711540	02
RD04	TN4 – Electrical Analyses	0005-0016616955	02
RD05	TN5- Mass Properties and Envelop	0005-0016699396	01
RD06	TN6 – Design of Breadboard	0005-0017754749	01
RD07	TN7 – Test Plans and Procedures	0005-0018693636	01

RD08	TN8 – Test Results	0005-0018693664	01
RD09	TN9 - Consolidated Design Description	0005-0018697286	01
RD10	TN10 – Preliminary Cost Estimation	0005-0018896086	01

1.5 ABBREVIATIONS AND DEFINITIONS

AIT	Assembly, Integration and Test
BBM	Bread Board Model
PM	Power ModuleRD02
PVA	Photovoltaic Assembly
RFSA	Rollable Flexible Solar Assembly
SA	Solar Array
TAS-F	Thales Alenia Space, France
TS	Tape spring

2. PROJECT'S GOALS

In this section the background related to high performance flexible solar arrays is presented, including the description of Thales Alenia Space perspective. This section also defines and clarifies the objective of the activity in the form of a statement.

2.1 BACKGROUND

In recent years, constellations have been developed, to provide satellite internet access. The SpaceX Starlink constellation, for instance, comprises thousands of spacecraft. Spacecraft of this sort are typically 200-300 kg in mass and operate at some 500 – 600 km altitude. Solar arrays are typically 20 - 30 m2 in area and around 5 kW in power.
In recent years, much progress has been made in the development of high performance solar arrays, primarily for GEO applications. The fully flexible variant of Thales comprises blankets, onto which the photovoltaic assembly is bonded, supported by a pair of tape springs on either side. The semi-flexible variant of Airbus consists of a backbone of conventional rigid panels, supporting semi-flexible panels deployed laterally. More recently, studies have been performed to assess the suitability of these concepts for exploration missions, but no such assessment has been made for adaptation to LEO constellation applications.
Other concepts, incorporating flexible blankets, include the Ultraflex array of Northrup Grumman, of which the Next Generation Ultraflex is a variant. It comprises a flexible-blanket accordion-folded lightweight membrane that is deployed to a tensioned and rigid pre-loaded structure, similar to a shallow umbrella.

2.2 OBJECTIVE(S) OF THE ACTIVITY

This study has been performed in order to assess the suitability of the SolarFlex concept for adaptation to LEO constellation applications:

- with power requirements up to 5 kW.
- with low in cost
- which can be packed tightly into limited stowed volumes (target range 25-40 kW/m3).

The target Technology Readiness Level (TRL) is 4.

3. PROJECT METHODS AND PROGRESSING

In this section the methods and way of progress on a project are described, taking into account crucial and critical incremental steps.

3.1 PROJECT WORK FLOW AND TIMELINE

This activity is divided in tasks. The activity encompasses the following tasks:

- Investigation of different deployment schemes.
- Preliminary design of solar array concept.
- Prediction of electrical performance.
- Performing mechanical analyses, in order to assess strength, stiffness and deployment dynamics.
- Deriving estimates of mass and inertia.
- Designing, manufacturing and testing of breadboard models, in order to verify the preliminary feasibility of the solar array concept (deployment concept).

The aforementioned tasks are gathered together on the basis of development processes to provide a structure to the project. Finally the project is characterized by the following 4 Work Packages (“WPs”):

- WP1: *Flexible SA Concept Trade-off*, focused on the investigation of different deployment schemes.
- WP2: *Flexible SA design and analysis*, focused on the:
  - preliminary design of solar array concept.
  - prediction of electrical performance.
  - mechanical analyses.
  - estimation of mass and inertia.
- WP3: *Flexible SA Breadboard Design & MAIT*, focused on the design, manufacturing and testing of breadboard models.
- WP4: *Flexible SA consolidated design & perspectives,* focused on the conclusions and way-forwards

The following flow chart presents the project broken into the aforementioned WPs, highlighting the crucial networks among them and the proposed Deliverable Items List (“DIL”) used to state the acceptance of the project progressing during formal review events.

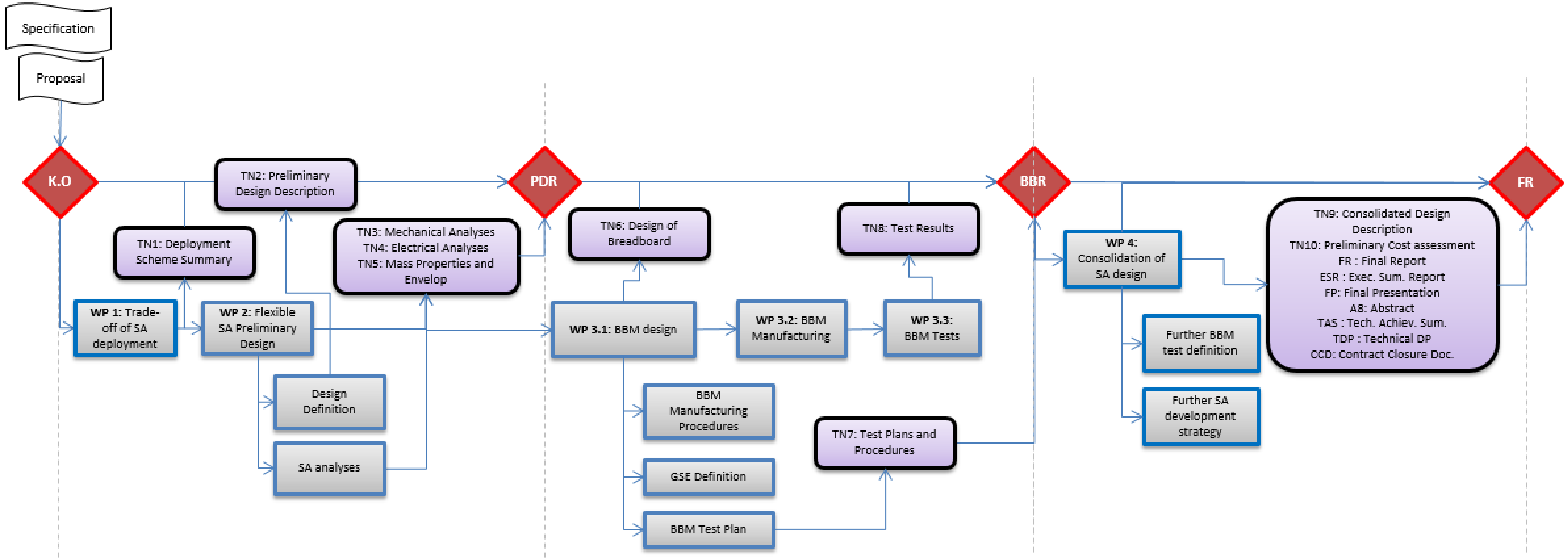


Figure 3-1 : Work Flow

The following presents the timelines of the project including information about meetings, reviews and milestone events.

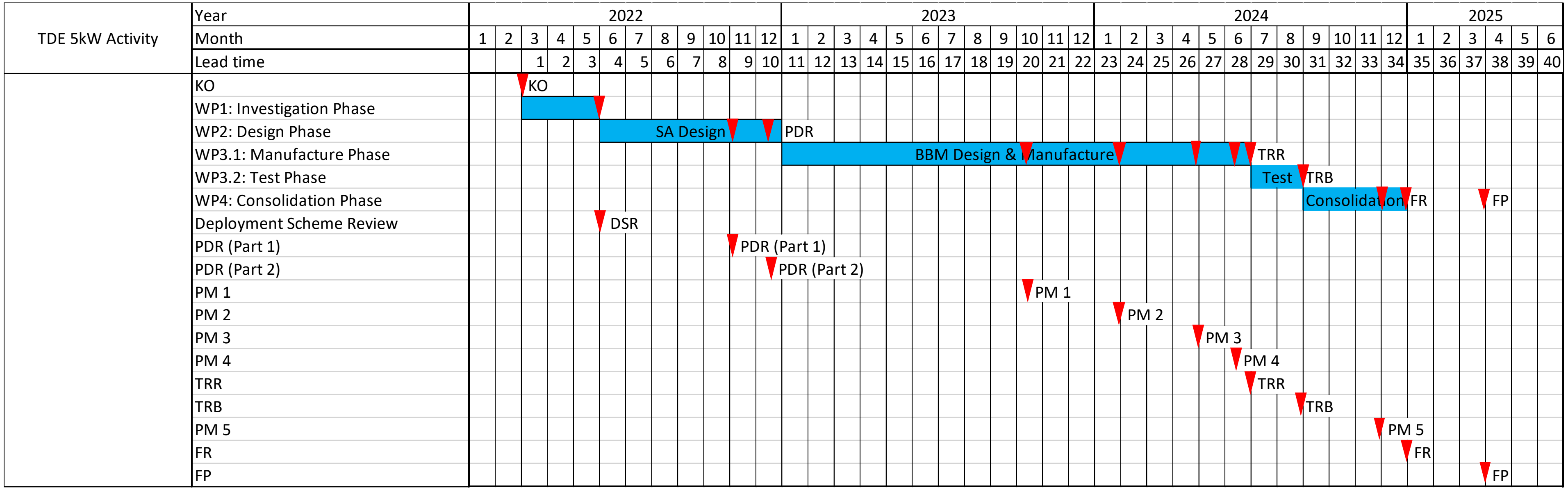


Figure 3-2 : Project Timeline

(*) Note : Lead time is the amount of time that passes from the start of a process until its conclusion.

3.2 PROJECT ORGANIZATION AND COMMUNICATION LINES

Participating companies involved in this project are:

- Thales Alenia Space – France (the Prime Contractor) (hereby called “TAS-F” as short name) for the design, assembly and test (as defined by the WPs 1, 2, 3 and 4)
- 5M s.r.o. (the Sub-contrator) (hereby called “5M” as short name) for the manufacturing (as defined by the WP3; to be noted: only related to the BBM manufacturing)

The applied Organizational Breakdown Structure (OBS) is presented hereunder in the form of a diagram taking into account the WPs and Key Personnel. The communication line to ESA is also included in the diagram.

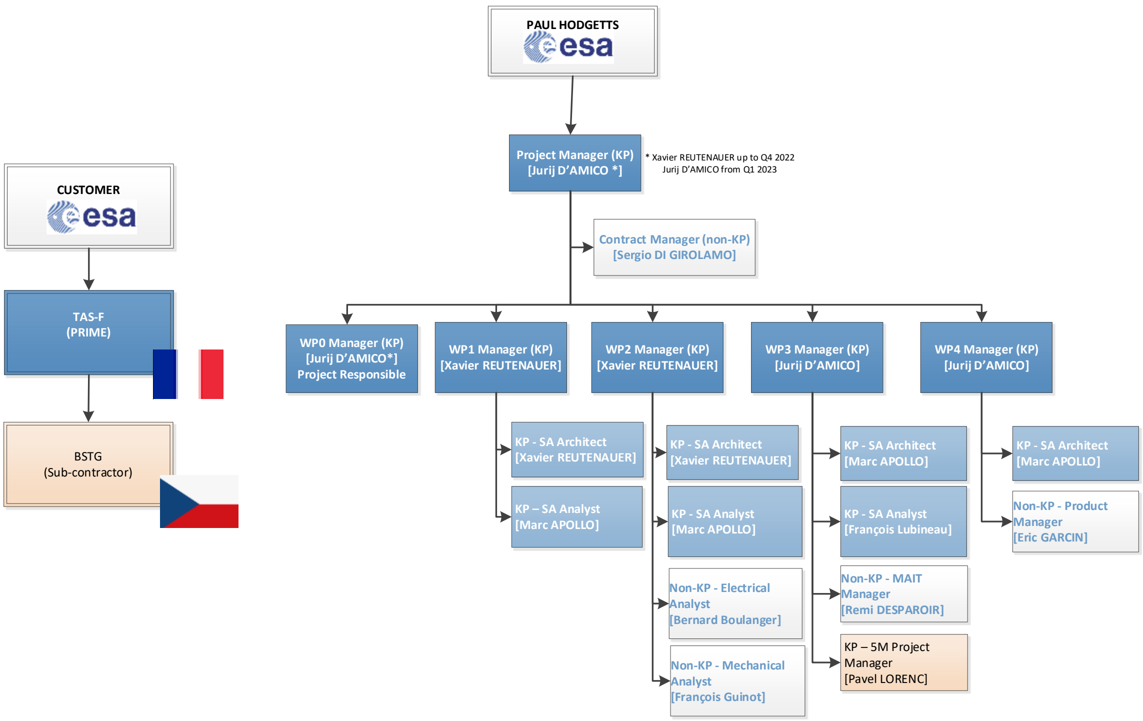


Figure 3-3 : Project OBS

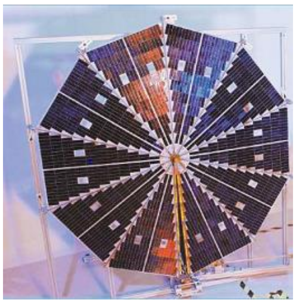
3.3 WP1 PROGRESS HIGHLIGHTS: INVESTIGATION OF ARRAY DEPLOYMENT SCHEME

3.3.1 WP1 Main facts

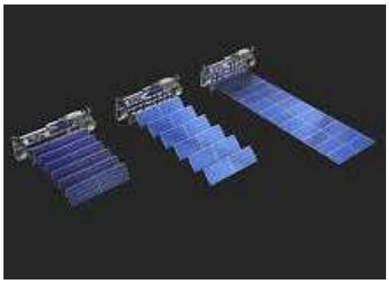
This phase has included the following tasks:

- Review of the hypothesis for constellation S/C architecture
- Review of the SA functional and technical specification
- Analysis of performances versus power (up to 5kW) for the following 4 selected candidates:
  - Candidate 1: Fan folded solar array
  - Candidate 2: Accordion SA with central mast deployment on panel rear face
  - Candidate 3: Accordion SA with central mast deployment
  - Candidate 4: Roll out SA with tape spring for deployment
- Trade-off between candidates
- Selection of candidate 4 (roll out solar array) as most promising solution

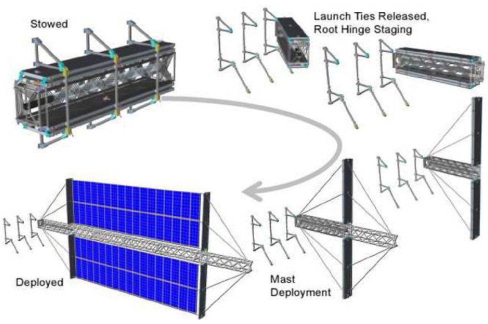
In particular, four solar array deployment structures were assessed for application to "New Space" constellation satellite up to 5kW EOL. The characteristics and performances of these candidates were evaluated in terms of mass, stowed volume, deployed volume, frequencies, AIT constraints and cost.



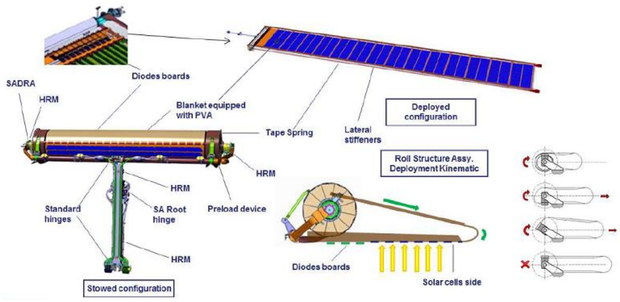
1: Fan folded solar array



2: Accordion SA with central mast deployment on panel rear face



3: Accordion SA with central mast deployment on panel rear face



4: Roll out SA with tape spring for deployment

Figure 3-4 : Flexible SA Architectures

3.3.2 WP1 Main conclusions

From the trade-off, it appears that there is no candidate which perfectly fits all the requirements. The candidates 2 and 4 seem to be the best compromise for the considered application. Nevertheless, it has been emphasized that at the time of the bid TAS-F team was already developing a flexible SA, SOLARFLEX, for Space Inspire Program. Notably the SOLARFLEX concept/product is judged as an opportunity in the frame of the TDE project because of its design flexibility to several power requirement being a real advantage for developing a standard solar array family. Consequently the TAS-F team propose the selection of the candidate 4 fostering the adaptation of the SOLARFLEX product for missions up to 5kW. Also, the capability of partial deployment and folding could be of interest for specific missions. Finally, the new silicon solar cells which are issued from terrestrial market and which are now proposed/qualified for space market have the main advantage to be rollable on much smaller diameter than before, so the roll up SA design (candidate 4) could then benefit of this new technology. ESA agreed on the conclusion of the trade off and on the selection of candidate 4.

3.4 WP 2 PROGRESS HIGHLIGHTS: PRELIMINARY ARRAY DESIGN

3.4.1 WP2 Main facts

This phase has included the definition of a preliminary design of solar array concept based on mechanical analyses (assessing strength, stiffness and deployment dynamics), electrical performance analyses, as well as mass/inertia estimates and stowed envelope. The figure below shows the three-dimensional concept:

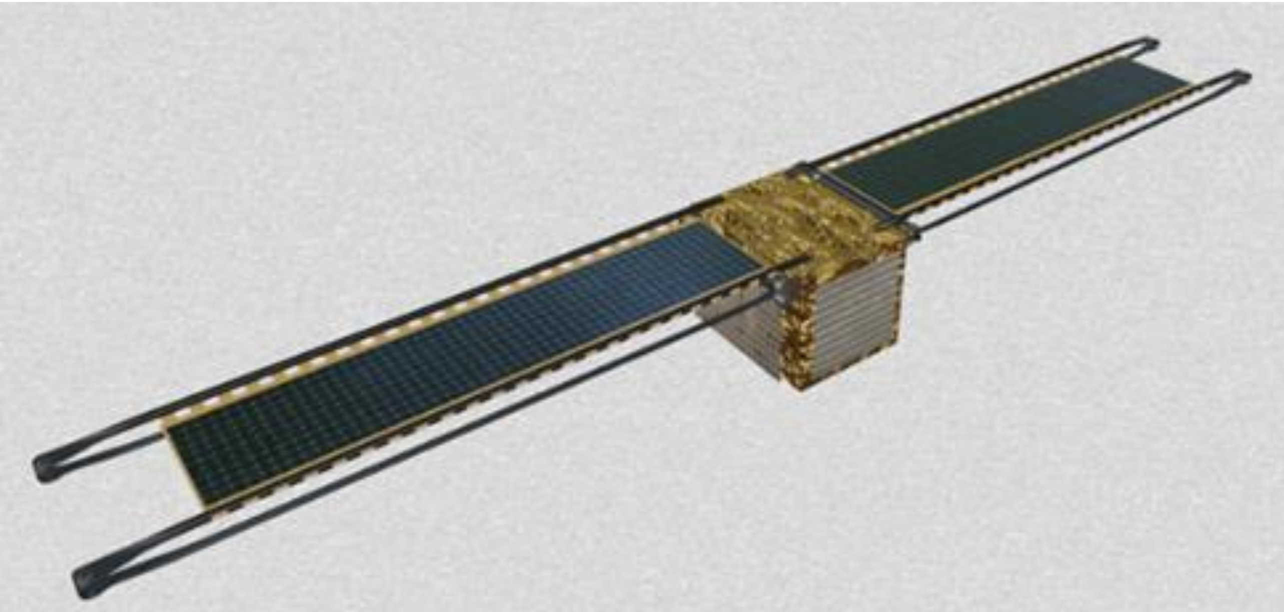
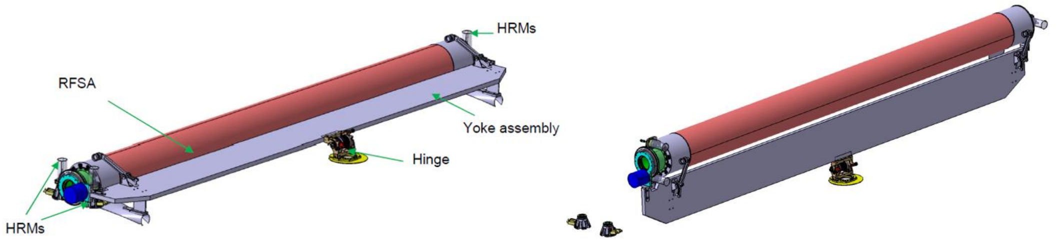


Figure 3-5 : Three-dimensional concept of Flexible SA Architecture proposed by TAS-F team in the frame of the project

The solar array is composed by:

- A hinge
- A yoke assembly
- A RFSA assembly
- HRMs

Hereunder are presented some views of the concept until full deployment, sequenced in 3 times:



Stowed configuration

Figure 3-6 : Intermediate configuration (90° yoke deployment) – after HRM release

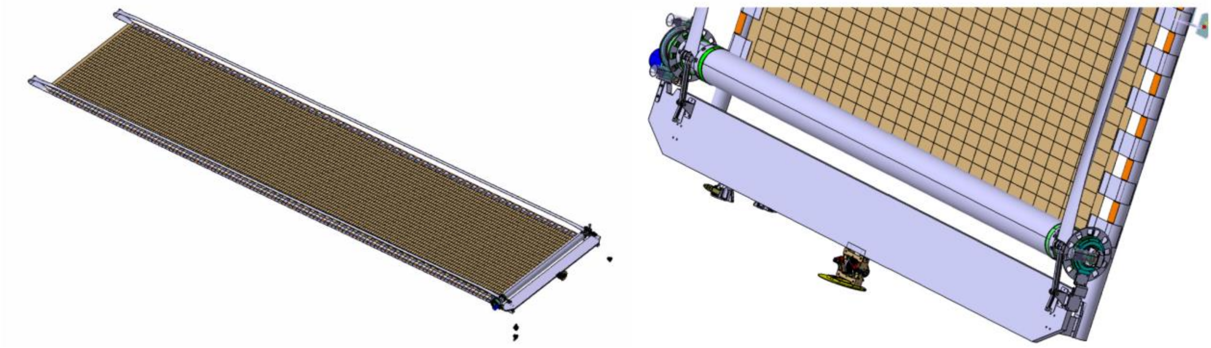


Figure 3-7 : Full deployed configuration

Compared to Solarflex, this architecture integrates new principles and components for achieving a better compactness, having all the necessary features to ensure a correct deployment function. The new principle are the following:

- The preload device (characterized by blades)
- A synchronization and release devices suitable for the existing gap between each tape spring layer and to allow a lower volume in stowed configuration:
    - fasteners (thickness is 0.93mm)
    - pins at mandrel level
- A Ø60mm tape spring (instead of Ø100mm on Solarflex), with 140mm width for the go side and 110mm width for the return side, complying the first mode needed

- Blankets reinforced with integrated stiffeners (transversal and longitudinal) (instead of external rigid stiffeners) complying the 1st deployed mode as long as compatibility with limited space/gap (0.93mm) between each TS coils.
- Ears fasteners fixed at the extremity of the tape spring to insert a natural tensioning of the blanket during deployment

3.4.2 WP2 Main conclusions

Based on a preliminary array design, the Thales team has demonstrated the feasibility of the development of a fully flexible variant of SolarFlex product characterized by two 3x10 meters wings delivering each one at End Of Life 2.85 kW (considering silicon cell) or 4.9 kW (considering AsGa cell) which can be packed tightly into an extremely limited stowed volume with a range equal to 33 kW/m3 (silicon) or 57 kW/m3 (AsGa) with a power to Mass Ratio equal to 57 W/Kg (silicon) or 98 W/Kg (AsGa).
The compliance status of the proposed design (at the end of the WP2) with respect to the main requirements is presented below.

Requirements		specification	Status	comments
Req-1	SA power (2 wings)	5KW EOL	C	See TN1
Req-2	Maximal dimensions *Stowed configuration*	Width: 3000mm maximum compacity for other directions	C	See TN5
Req-3	Maximal dimensions *Deployed configuration*	Width: 3000mm Length : as low as possible to limit inertia	C	See TN5
Req- 4	Inertia and CoG position *Deployed configuration*	As close as possible of the S/C (no specific requirement from AOCS)	C	See TN5
Req- 5	Mass	50Kg max with AsGa cells 70Kg max with Silicon cells	C	See TN5
Req- 6	Nominal first eigen frequencies *Stowed configuration*	>35Hz	C	See TN3
Req- 7	Nominal first eigen frequencies *Deployed configuration*	>0.01Hz (electric propulsion)	C	See TN3
Req- 8	Blanket temperature range	[-120°c;+120°c]	C at blanket level	NC for fasteners (terrestrial product)
Req-9	Mechanical loads	Refer to AD2 – Appendix A	NC	See TN3
Req- 10	AIT constraints	Deployable on ground in horizontal configuration	C	
Req- 11	AIT - PVA Interchangeability	PVA module could be replaced or repaired in deployed configuration	C	Thanks to fasteners and ears principle
Req- 12	AIT – PVA folding/rolling-up after deployment on ground	Flight representativeness shall be guaranteed by design after folding/rolling-up	C	Thanks to fasteners repeatability
Req 13	SA folding capability in flight	Not requested for LEO constellation	NA	
Req-14	Mechanical interfaces	Interfaces with S/C structure	C	Yoke/SADM I/F has been integrated

Figure 3-8 : Compliance matrix (wrt the functional and technical specifications)

3.5 WP 3 PROGRESS HIGHLIGHTS: BREADBOARD MODEL MANUFACTURE AND TEST CAMPAIGN

3.5.1 WP3 Main facts

This phase has included the following tasks:

- Design of a solar array breadboard able to validate the flexible solar array flight model's deployment function
- Design a GSE for breadboard testing including all the ground-based elements of the BBM used by operators to both allow the assembly and support personnel during test and measurements.
- Definition of the BB assembly and deployment procedures and test sequence
- Manufacturing of the BB and GSE
- Assembly of the BB, GSE and test set-up
- Execution of the test including summary of the test results

The breadboard has been designed to be deployed both horizontally or vertically with a solar array deployment test set-up using the existing 0-g facility in Cannes. The breadboard is fully representative of the deployment function of the flight system version of the solar array and it is composed by the following two main assemblies:

- A Rollable Flexible Solar Assembly (RFSA) (mobile part)
- An equipped structure (fixed part)

The following table presents the set of sub-systems of the two assemblies:

Breadboard Assembly	Breadboard Subsystems
RFSA Assembly	Tape Spring
	Blanket
	Dummies
	Fastener
	Mandrel
	Synchronisation pins
Equipped structure	Preload devices
	Tape spring anchorage
	Motorization unit

Table 3-9 : Breadboard Subsystems list

Hereunder the Breadboard assemblies are presented in both stowed and deployed configurations.

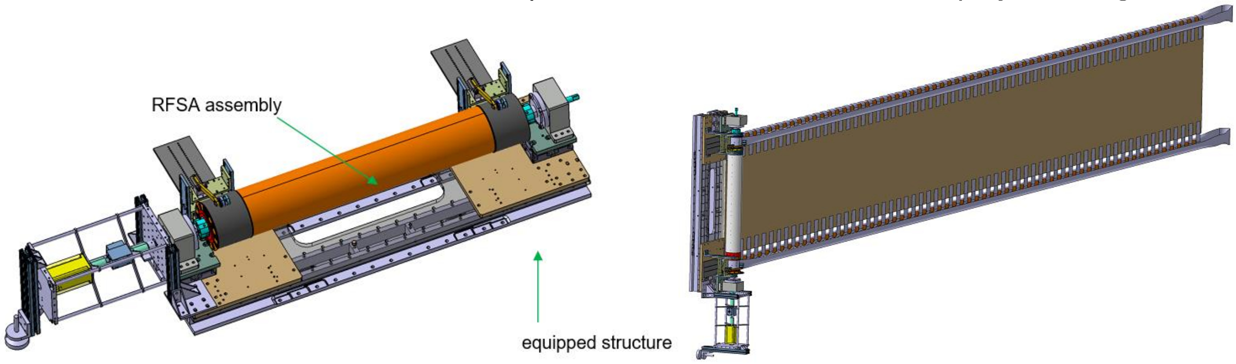


Figure 3-10 : Breadboard assembly in stowed and deployed configurations

A specific structure has been designed for allowing the assembly of the breadboard. This structure facilitates:

- the integration of Fasteners on TS
- the synchronization of TS with each other
- the integration of the blanket
- the binding between TS and blanket

The figure below shows the three-dimensional (3-D) model of the BB integration/assembly setup:

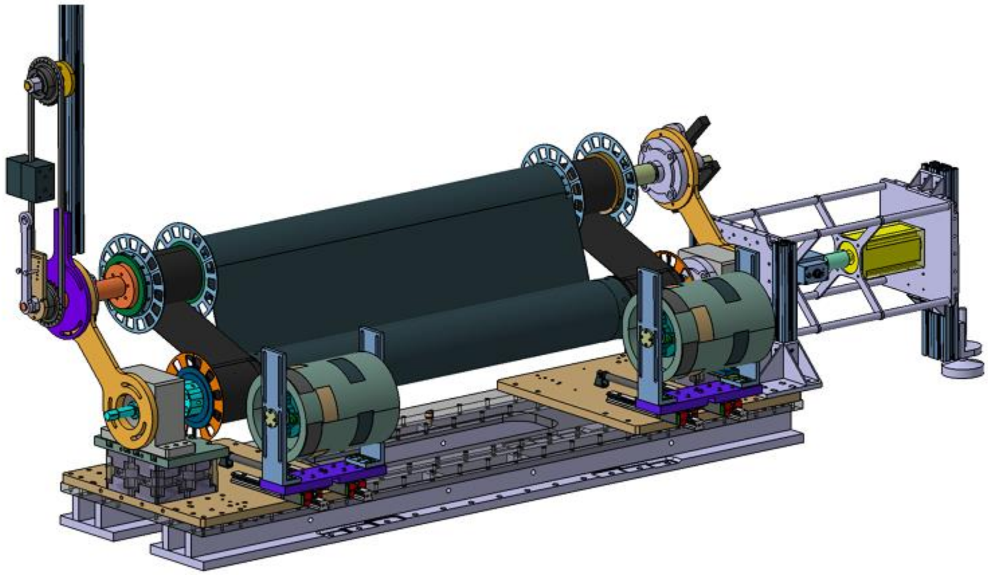


Figure 3-11 : Three-dimensional (3-D) model of the BB integration/assembly setup

Thales Alenia Space team has taken benefits of the Fablab Innovation Cluster with specific equipment and tooling such as 3D printing, additive manufacturing and small team working in a start-up mind-set, to study the topics of the project. TAS-F Cannes team has focused the attention on Mechanisms, deployable and moving structures of the BBM.

The approach of the Fablab cluster is to build and to test easily with homemade prototypes some new concepts, for instance derived from terrestrial technologies and to be adapted to Space field. It is the case of Preload device and fasteners manufacturing and testing. Main advantage of the Fablab mind-set was to be capable of concretizing ideas quickly and share knowledge with ESA.

The communication was also facilitated towards customer and project teams since physical prototypes have been presented rather than papers or 2D/3D modelling. The validation of the preliminary concept of preload device, tape spring and synchronization devices have been also eased and more efficient with a better perception of physics, moving parts and assembly problematic.

Fablab was used for the roll-out BBM assembly to test feasibility of the assembly procedure notably for the deployment of structure with regards to the tape springs and blankets. Figure is provided below as example of Fablab activities dedicated to SA BBM assembly using the real integration/assembly setup.

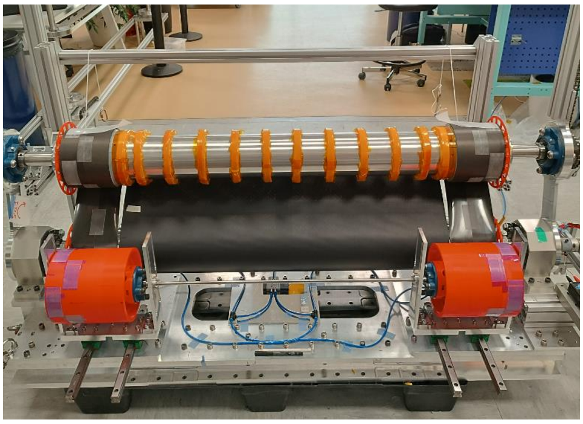


Figure 3-12 : BB integration/assembly setup view in Fablab

For the purposes of this project the involvement of 5M team was beneficial notably for the manufacturing of the mechanical and flexible parts (including tape springs and blankets). Their available clean rooms and testing facilities were used for elementary tests as well. All needed capacity for expected testing were well covered by 5M team.

Once BB assembled in Fablab, the TAS-F team was ready to move the BB into the clean rooms. The figure below shows the breadboard already assembled and ready for test, integrated on 0G trolley placed in the clean room under rails.

Figure 3-13 : View of BB assembly in clean rooms

The SA has been deployed thanks to loops attached to the TS. Loops are attached on 0g rails which slide to follow the deployment as shown in the figures below.

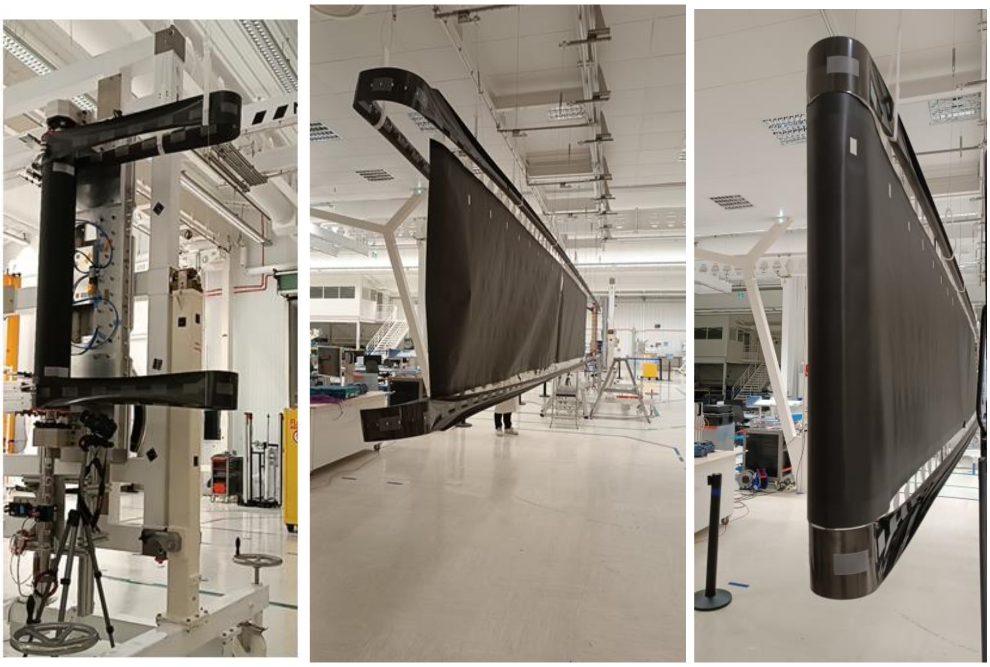


Figure 3-14 : View of BB assembly during deployment test

3.5.2 WP3 Main conclusions

Several deployment tests have been performed to establish whether each technological building block works and contributes as per the deployment requirements. Each BB system has been judged compared to the corresponding contribution to the functional requirement to verify whether its operational mode is consistent with the end user's expectations. An high confidence on the suitability of the proposed innovative technologies for deployment has been built. It is the case of preload devices characterized by blades, synchronization and deployment devices based on fasteners and pins. However some anomalies on the blankets (folds during deployments and through the bulb passage) have been observed. The table below shows the summary of the conclusions during the visual inspection of the test.

Breadboard Subsystems	Pros	Cons
Tape Spring	The action of bringing TS from stowed to deployed configuration is achieved under motorization **Deployment ☺**	The diameter reduction (from Ø100mm on Solarflex to Ø60mm) induces a lower stiffness when the TS passes through the bulb (folds on blanket visible during the test due to misalignment between the 2 TS) **Stiffness 😐**
Blanket with longitudinal stiffeners	The action of bringing blanket from stowed to deployed configuration is achieved under motorization action. Longitudinal stiffeners improve the behaviour of the blanket in bulb area **Deployment ☺**	The variable stiffness along the longitudinal direction of the blanket (due to the lateral reinforcement) creates some local folds at bulb level **Stiffness ☹**
Blanket with integrated lateral reinforcement	The action of bringing blanket from stowed to deployed configuration is achieved under motorization action **Deployment ☺**	The stiffness of the integrated lateral reinforcement is insufficient to guarantee the correct alignment between the 2 TS and as consequence the correct blanket flatness. Added rigid stiffeners are mandatory to avoid folds when blanket passes through the bulb. **Stiffness ☹**
Fastener	The fasteners have been unclipped as expected, with only the use of tape spring transversal motorization. Good behaviours for go portion with the estimated pre-load force **Deployment ☺**	Fasteners system could not be compatible with numbers and positioning of these stiffeners. **Compatibility with added rigid stiffeners ☹**
Mandrel	Mandrel has correctly linked the 2 Tape springs and unroll properly the blankets under motorization action **Deployment ☺**	None
Synchronisation pins	The principle has worked well during 1,6m without any human intervention. Pins and holes was not in contact. **Deployment up to 1,6 m ☺**	Interference between pins and holes from 1.6m to 3m (delamination occurs) Pins and holes was not in contact due to the inconsistency between the hole drilling and TS thickness .- **Deployment from 1.6m ☹**
Preload devices	No tape spring swelling during deployment under the preload force action	None

	Deployment ☺	
Tape spring anchorage	Tape springs were correctly linked to the fixed structure during deployment under motorization action. The anchorage insure the correct TS stiffness **Deployment** ☺	None

Figure 3-15 : Main conclusions of the SA BB deployment functional test

Each BB system has been judged compared to their contribution to the SA compactness.

Breadboard Subsystems	Pros	Cons
Tape Spring, Blanket, Mandrel, Fastener	This project has allowed to confirm the feasibility of a miniaturized version of the SolarFlex product for low power (2,5 kW for 3x10 meters wing). Notably the BBM carried out on this study shows an evident compactness in stowed configuration. **Compactness** ☺	None

Figure 3-16 : Main conclusions of the SA BB compactness

In conclusion, to overcome the visible anomalies on the blankets (folds during deployments and through the bulb passage), a design optimization and additional tests are recommended, in order to improve the tensioning and flatness of the blankets and co-alignments of the tapes springs.

3.6 WP 4 PROGRESS HIGHLIGHTS: CONSOLIDATED ARRAY DESIGN AND PRELIMINARY COST ANALYSIS

3.6.1 WP4 Main facts

This phase has included the following tasks:

- The review of steps of the risk management process using outcomes from BB testing.
- The identification of a new problem solving plan associated to the risks considered within the project.
- A preliminary analysis of the SA design improvements based on outcomes from BB additional testing.
- A preliminary cost assessment for improving actions that can be implemented in short term having the positive impact on the consolidation of a TRL equal to 4.
- A preliminary cost assessment for further developments (mainly focused on mechanical aspects)

At the time of the bid for the [AD02], [AD03], TAS-F team have identified the main risks for the project based on brainstorming and standard checklists. Among all the risks the following ones have been evaluated with the highest severity and occurrence probability against the possible overall project consequences (cost, schedule, overrun, quality customer satisfaction):

- **RISK 1:** Risk that deployment system is not mature enough and deployment sequence fail
- **RISK 3:** Risk to overpass SA mass target, notably in W/kg
- **RISK 4:** Risk to not fulfill the 1st mode frequency in stowed and in deployed configurations
- **RISK 10:** Risk that flexible SA development up to TRL4 is delayed if retained solution is totally new (without any development heritage)
- **RISK 12**: Risk that AIT tooling and test means are not adapted to SA new design leading to over non-recurring costs and schedule delay (e.g. 0g deployment).

Mitigation actions were already identified and proposed in the risk identification register at the time of the bid. The successful accomplishment of the WP3 is considered the most important action to mitigate the RISK 1 and 12. The successful accomplishment of the WP2 is considered the most important action to mitigate the RISK 3 and 4. The implementation of a roll-out solution based on SOLARFLEX heritage is considered the most important action to mitigate the RISK 4. The table below shows the status of the risk management process at the end of the project (to be noted: the mitigation actions in the table are the ones proposed during the bidding and project progress phases).

Risk	Domain	Risk Scenario	Mitigation activities proposed during the bidding phase	Status
Risk 1	TECH	Risk that deployment system is not mature enough and deployment sequence fail.	To perform design and deployment analyses during project development. To design a BBM testing the SA deployment system to ensure its function.	This risk has been reviewed using outcomes from BB testing and a new detailed problem solving plan has been proposed accordingly in order to solve the observed anomalies. **Risk managed but not totally mitigated**
Risk 3	TECH	Risk to overpass SA mass target, notably in W/kg	To perform a trade-off between lightweight structural parts and PVA. To perform mass saving study.	At this stage, the solar array is near to 50kg (one wing) for 2.5kW and corresponds approximately to 50W/kg with silicon cells. Mass requirements allowed a maximum mass of 50kg with Asga cells and 70kg with Silicon cells. Risk mitigated. **Risk mitigated**
Risk 4	TECH	Risk to not fulfill the 1st mode frequency in stowed and in deployed configurations	To perform mechanical sizing of SA and notably modal analysis in stowed and in deployed configuration.	-In stowed configuration: the first mode calculated is 41,86Hz (specification >35Hz) -In deployed configuration: the first mode is 0,085Hz (specification >0,01Hz), without stiffeners Risk mitigated providing that no external rigid stiffeners are used. **Risk mitigated**
Risk 10	PROG	Risk that flexible SA development up to TRL4 is delayed if retained solution is totally new (without any development heritage)	Schedule impact to be addressed during trade-off phase on flexible SA solutions to discard those which cannot reach TRL4 until 18 months development phase duration.	The BBM carried out on this study shows that an increase in compactness is achievable. However the actions implemented cannot draw any definitive conclusion on the deployment function with a TRL=4. A clear list of problem solving actions are identify thanks to the heritage of the project. Quick wins can be highlighted. **Risk mitigated**

Risk	Domain	Risk Scenario	Mitigation activities proposed during the bidding phase	Status
Risk 12	PROG	Risk that AIT tooling and test means are not adapted to SA new design leading to over non-recurring costs and schedule delay (e.g. 0g deployment).	To assess adaptability of SA design on test means during trade-off phase. If needed to develop 0g deployment jig.	This risk has been reviewed using outcomes from BB assembly and a new problem solving plan has been proposed accordingly. However new AIT tooling are still needed. **Risk managed but not totally mitigated**

Figure 3-17 : Risk Analysis

The table below shows the new mitigation actions plan for the risks 1 and 12 (with the highest severity and occurrence probability) as along with the proposed implementation opportunities and costs to reach the TRL4.

Risk	Point	Domain	Problem Description	Mitigation strategy	Action/cost for improvement	Opportunity for Implementation
Risk 1 / Risk 12	Point 1	Flexible GS BBM Integration/Assembly	Difficulties were encountered during BBM assembly process in stowed configuration (misalignments and synchronization problem between BBM components along the thickness and through the deployment axis)	Integration/Assembly in deployed configuration seems mandatory, including rigid stiffeners in the assembly process	Design, manufacturing and integration/assembly of a tool for the BBM assembly in deployed configuration to allow a best control of the distance between tape springs and integrate properly the blankets (estimated cost: **70 k€**)	Action considered within the TAS-F proposal in response to ESA ITT for "Flexible Solar Array for Lunar Pole Applications" ref.: ESA AO/1-12473/24/NL/MGu.
Risk 1	Point 2	Flexible GS BBM Synchronization System Functioning	Operation problem was encountered during the assessment of the synchronization systems functioning (for back side) (misalignments between TS holes and pins locations due to TS manufacturing defects)	Control of the TS drilling plan based on better TS thickness prediction	Definition of TS technical drawings and manufacturing and drilling of tape springs to test the synchronization system using pins (or conical cups) (estimated cost: **55 k€**)	Action considered within the in progress activities: SolarFlex project and the TDE ESA AO/1-11161/22/NL/FE for the development of "New type of flexible solar array for lander or rover applications"
	Points 3 and 4	Flexible GS BBM Fasteners developments	Space material for fasteners is not available. Consequently a development is needed. Sizing of fasteners is simply based on preliminary experimental de-risking test done at TS level. Incompatibility with stiffeners positioning.	Consolidation of the fasteners development strategy based on suitability with numbers and positions of external rigid stiffeners (see problems 4 and 5).	-Mold/fasteners Manufacturing, Mechanical and thermal characterization (**50 k€**) -Manufacturing of new fasteners system using pins (or conical cups) (**16,5 k€**) -Manufacturing and static test of gutter to be implemented on the blanket for decreasing level of lunch load on fasteners. (**20 k€**)	Concerning characterization, action considered within a dedicated ESA OSIP Concerning conical cups, action considered within the TAS-F proposal in response to ESA ITT for "Flexible Solar Array for Lunar Pole Applications" ref.: ESA AO/1-12473/24/NL/MGu. Concerning the gutter, action partially considered within the TAS-F proposal in response to ESA ITT for "Flexible Solar Array for Lunar Pole Applications" ref.: ESA AO/1-12473/24/NL/MGu and partially considered within the ARTES AT CRITICAL BUILDING BLOCKS FOR FUTURE LIGHTWEIGHT FLEXIBLE SOLAR ARRAY ref.: AO/1-10691/21/UK/ND

Risk	Point	Domain	Problem Description	Mitigation strategy	Action/cost for improvement	Opportunity for Implementation
	Point 5	Flexible GS BBM deployment (TS positioning during deployment)	Deployment problem of the TS observed from the unsuitable positioning of the GS (not controlled spacing between TS)	Replacement of stiffeners integrated/embedded in the blanket with external rigid stiffeners including an optimal BBM integration plan.	-Manufacturing and Integration of rigid stiffeners with new fixation principle (**9 k€**) -Design, Manufacturing and integration of new blanket with longitudinal stiffeners (**27 k€**)	Action partially considered within the in progress TDE ESA AO/1-11161/22/NL/FE for the development of "New type of flexible solar array for lander or rover applications" (Note: only deployment and not rolling phase)
	Point 6	Flexible GS BBM deployment (Blanket positioning during deployment)	Deployment problem of the blanket observed through the bulb passage (Blanket folds appears)			
	Point 7	SA positioning during rolling	Rolling problem of the GS observed from the unsuitable synchronization of the TS and insufficient effort on preload system	Improvement of synchronization system (with pins) and preload devices (with additional rollers).	-Design, manufacturing, integration and test of new preload including more rollers (**30 k€**)	Action considered within the TAS-F proposal in response to ESA ITT for "Flexible Solar Array for Lunar Pole Applications" ref.: ESA AO/1-12473/24/NL/MGu.
	Point 8	SA Global Architecture	Integrated Y stiffeners in blankets and blanket ears are not suitable to avoid problem during deployment (see points 5 and 6).	The integration of external rigid stiffeners is essential as long as the critical evaluation of their compatibility with fasteners and other possible impact on the design for their fixation	- Review of compactness to analyze the compatibility between rigid stiffeners, fasteners and tape springs. (**15 k€**)	Action considered within the TAS-F proposal in response to ESA ITT for "Flexible Solar Array for Lunar Pole Applications" ref.: ESA AO/1-12473/24/NL/MGu.

Figure 3-18 : Updated Risk Analysis (Development Plan for TRL=4)

Assuming the achievement of the TRL4 (based on the accomplishment of the aforementioned mitigation actions plan), the table below presents a further step of the development in order to reach the TRL5 (implementation opportunities and costs are highlighted as well).

Risk	Domain	Problem Description	Mitigation strategy	Action/cost for improvement	Opportunity for Implementation
Risk 2	SA Global performance under vibration	Risk that SA design is not compatible with PVA allowed dynamics deformation and vibration loads (e.g. Contact between PVA and structural parts strength or between PVA parts; deployment shocks.).	Vibration test to be performed using the upgraded version of the 5kW BBM (Note: upgraded version is derived from the implementation of the complete list of risk 1 mitigation actions)	- SA detailed design and analysis (**109 k€**) - SA BBM Manufacturing and integration/assembly (**41 k€**) (Blanket and mandrel only with mandrel made in carbon + cells gluing on blanket) - SA BBM procurement (only cells dummies and PVA) (**56 k€**) - Vibration test campaign (including definition of BB test specifications and procedures; design of GSE, assembly of the test bench; execution of BBM tests in TASF premises; synthesis of the tests results) (**140 k€**)	Action considered within a possible ESA GSTP

Figure 3-19 : Updated Risk Analysis (Development Plan for TRL=5)

3.6.2 WP4 Main conclusions

The opportunities for placing a miniaturized SolarFlex product within the market of small/medium solar array for LEO constellation seems to be real. Promising work is in progress to optimize the SA architecture in a cost efficient way and to explore concrete opportunities to increase the TRL up to 5. In particular, after the deployment tests phase, some mitigation actions have been implemented, by additional testing procedures, to work on anomalies encountered during the deployment test.In particular:

- Deployment test with the integration of rigid stiffeners (to mitigate Points 5 and 6)
- Increase of preload effort (to mitigate the Point 7)

On the next phase, improvements could be realised using the available BBM to limit costs. To consolidate and increase TRL level, the following development plan could be implemented:

- Develop the tool for an assembly in deployed to allow a best control of the distance between tape springs and integrate properly the blankets (Point 1)
- Manufacture new tape springs with a work on thickness improvement to test synchronization pins system (Point 2)
- Integrate rigid stiffeners with new fixation principle (Point 5)
- Manufacture blanket with longitudinal stiffeners (Point 6)
- Modify the preload to add more rollers (Point 7)
- Review architecture to manage (Point 8):
  - the rigid stiffeners consequence with fasteners
  - the fixation between blanket, rigid stiffeners and tape springs

3.7 PROJECT MANAGEMENT CHALLENGES: MAIN ISSUES, RISKS AND OPPORTUNITIES

An example of project dashboard defined during the activity is presented below. It is a single table that presents at a glance how the mains issues corresponding to the main project management indicators have been processed and in which project timeline. Notably the table shows the issues that cannot be solved uniquely by the technical referents and needed the attention of the top management (project and product managers) including the following aspects:

- **Project Organization and planning:** Project organization is a central aspect of project management and refers to the structuring and coordination of all activities and resources within a project in order to consolidate the technical baseline at all the life cycle of the project.
- **Stakeholder management**: it is the process by which you organize, monitor and improve your relationships with your stakeholders. It involves systematically identifying stakeholders; analyzing their needs and expectations; and planning and implementing various tasks to engage with them.
- **Cost estimation and control:** it is the process of forecasting and controlling the financial and other resources needed to complete a project within a defined scope.
- **Planning estimation and control:** it is the process of forecasting and controlling the period needed to complete a project within a defined scope.
- **Risk and opportunity management:** it is a comprehensive description of the processes in place to manage a project's Risks and Opportunities (R&O). It includes the role of various project stakeholders, steering, and decision-making bodies; the tools used; what reporting is planned.
- **Change management:** Change management is defined as the methods and manners in which a company describes and implements change within both its internal and external processes.

Project Indicators	Major Issues	Quick wins
Project Organization and planning	**Q2-Q3 2024:** The assembly phase of the Breadboard has taken longer than expected due to some criticalities/complexity related to the integration of its sub-systems (tape spring and blanket). Consequently during the assembly phase the technical baseline has been reviewed and the assembly process has been kept thanks the application and validity of a problem solving plan.	Comparison of different flexible solar arrays assembly approaches (in both stowed and deployed configurations)
Stakeholder management	**Q2-Q3 2024:** The customer (ESA) has been involved systematically during all the life cycle of the project, increasing the exchange / relationships during the most crucial periods (e.g.: 3 Progress meetings in 2 months during the assembly phase to implement various tasks and/or mitigation actions with the ESA agreements).	A final presentation is envisaged in Q1 2025 at ESA/ESTEC premises.
Cost estimation and control	The process put in place in **Q3 2024** to control and absorb most of the expenses needed to accomplish the assembly of the BBM, because his unexpected complexity.	REX is taken into account for new bidding for ESA ITT related to flexible GS development.
Planning estimation and control	The process put in place in **Q3 2024** to control and absorb the delay due to the accomplishment of the mitigation action plan to solve the encountered problem during the assembly phase.	REX is taken into account for new bidding for ESA ITT related to flexible GS development.
Risk and opportunity management	**Q4 2024:** The processes in place to complete risk analysis using outcomes from BB testing.	To determine the costs associated to further development increasing TRL
Change management	**Q4 2024:** The manner to use the technical outcomes implementing them within the BID processes.	Opportunity to implement the GS improvements within the TAS-F BID process in response to recent ESA ITT (e.g.: for “Flexible Solar Array for Lunar Pole Applications” ref.: ESA AO/1-12473/24/NL/MGu)

Figure 3-20 : Project Management Dashboard

(*) Quick wins are solutions that can be implemented faster than others and have a positive impact on the organisation

4. PROJECT CONCLUSIONS

In this section the changes and effects taken place after implementing the project are presented. The conclusions are presented in terms of positive accomplishment already tangible for the space community and in terms of strategy for further developments

4.1 POSITIVE ACCOMPLISHMENT

Based on a preliminary array design and representative breadboard models, the Thales team has demonstrated the feasibility of the development of a fully flexible variant of SolarFlex product characterized by two 3x10 meters wings delivering each one at End Of Life 2.85 kW (considering silicon cell) or 4.9 kW (considering AsGa cell) which can be packed tightly into an extremely limited stowed volume with a range equal to 33 kW/m3 (silicon) or 57 kW/m3 (AsGa) with a power to Mass Ratio equal to 57 W/Kg (silicon) or 98 W/Kg (AsGa).
Moreover, for the first time, this miniaturized architecture has been tested in order to verify its deployment capability. An high confidence on the suitability of the proposed innovative technologies for deployment has been built. It is the case of preload devices characterized by blades, synchronization and deployment devices based on fasteners and pins. However to overcome visible anomalies on the blankets (folds during deployments and through the bulb passage) design optimization and additional tests are recommended, in order to improve the tensioning and flatness of the blankets and co-alignments of the tapes springs. Promising work is in progress to optimize the SA architecture in a cost efficient way and to explore concrete opportunities to increase the TRL up to 5.

This positive accomplishment has involved the capacity to work with ESA towards meaningful goals, the motivation to persist despite challenges and setbacks, and the achievement of competence and success in flexible GS domains.

4.2 STRATEGY FOR FURTHER DEVELOPMENTS

The Flexible SA development plan is based on the successful accomplishment of the qualification phase of the Solar Flex product of 1° generation as well as the accomplishment of the R&D activities currently in progress under ESA funding. The main focus of the TDE projects is to improve the technologies used on Solar Flex 1° generation for higher performances, including effective gain in terms of mass, power and compactness. In particular the TDE 5kW activity has allowed to demonstrate the effectiveness of the miniaturization of flexible SA for medium power constellations as well as the deploying capabilities. The figure below gives a global picture of the envisaged road-map presenting all the on-going ESA studies and perspective.

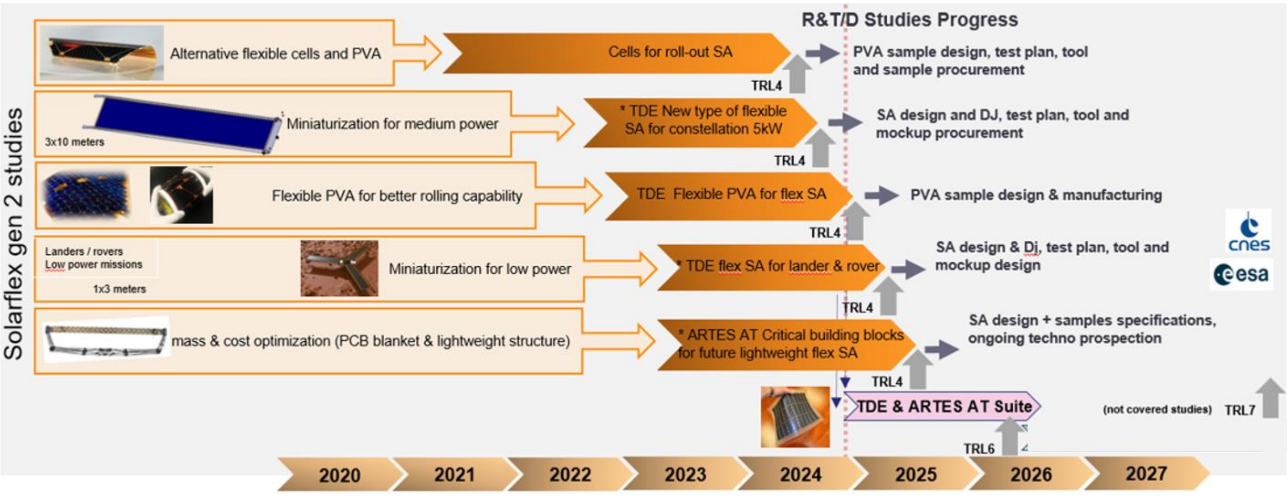


Figure 4-1 : SA Road Maps

The opportunities to test a Flexible SA in TAS facilities can push the way-forward according to the promising results and identified development plans. The validation of the SA global stiffeners and, in particular, the blanket behaviour when the blanket passes through the bulb are considered as one of the development priority. A possible stiffener solution has already shown the improvements with respect to the current architecture choices. However no definitive conclusion can be drawn. Additional test are needed.
Moreover, a deployment function synchronization using fasteners can be possible thanks to preload forces. However the synchronization function can be improved and an alternative solution by using pins mounted on the mandrel and holes on the TS has already shown the benefits with respect to the current architecture. Additional test are needed.

According to the aforementioned reasons, the development strategy can be summarized in two points:

- For SolarFlex SPI Gen 1.5 22 kW: Accomplishment of the SolarFlex SPI Gen 1.5 22 kW de-risking phase in 2025.
- For the second-generation flexible solar arrays: consolidation of TRL4 (by means of ESA TDE and ARTES) at the end of 2025 and TRL5 at the beginning of 2026.

END OF THE DOCUMENT