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SUMMARY

‘In–Orbit Manufacturing of Very Long Booms’
ESA Contract No. 4000115893/15/NL/RA/zk

The ‘In-Orbit Manufacturing of Very Long Booms’ (LMB) is a Magna Parva Ltd. (MPL) GSTP activity supported by the UK Space Agency under contract from the European Space Agency with the objective to develop a technology allowing the in-orbit manufacturing of very long, slender composite booms for large aperture applications. The activity included the realization of a prototype Breadboard (BB) Pultrusion Machine operated in vacuum, demonstrating the feasibility of the in-orbit boom production. Short length booms (length determined by test facility) were produced and mechanically tested.

The pultrusion process utilises a supply of fibre reinforcement tows and resin matrix system to manufacture (‘pultrude’) constant cross-section composite structures of nearly-indefinite length. The technology is most effectively employed in space system applications ~40 m, at which point conventional deployer technology is outperformed due to launch, test and operation constraints.

An existing miniaturised BB Pultrusion Machine was utilised to manufacture Carbon Fibre Reinforced Polymer (CFRP) Booms in ambient and vacuum environments. Test coupons were subsequently extracted and mechanical and material properties investigated (tensile, flexural, compressive, porosity, thermal, quality of cure). In most cases the Coefficient of Variation (CV) of data obtained approaches that of the production of aerospace primary structures in a commercial environment (4% to 10%). Further investigation in space-based pultrusion technology includes the improved control of fibre alignment and guidance.

The MPL in-space manufacturing technology within the context of this GSTP activity is at TRL3. External to this GSTP activity the technology has been developed to TRL4 and a LuxImpulse activity is in place to extend this to TRL6 by Q4 2018 at a cost of €2.5m which includes the development of the first application (a radio transmission interferometry/geolocation mission). The LuxImpulse activity and further exploitation of the MPL in-space manufacturing IP is through its mission-dedicated Luxembourg-based daughter company; Kleos Space S.a.r.l. Flight qualification for the technology is currently planned to be achieved through deployment on the first satellite of the radio transmission interferometry/geolocation mission at an estimated cost of €8.0m funded commercially and launched ~Q4 2019.

DISTRIBUTION

NAME	ORGANISATION
Alexander Ihle	European Space Agency

1.0 INTRODUCTION

The ‘In-Orbit Manufacture of Very Long Booms’ (LMB) project builds upon prior work conducted by Magna Parva Ltd. (MPL) in the field of space-based pultrusion systems. The LMB project aims to demonstrate the feasibility of in-orbit manufacture of very long booms by the design, manufacture and operation of a Breadboard (BB) Pultrusion Machine and the evaluation of the mechanical properties and variation of the booms produced thereof. The Executive Summary Report (ESR) summarises the findings of the study.

2.0 BACKGROUND

Many space applications require large structures in space. Typical examples include satellites for communications, earth observation, astronomy, and space exploration. Long booms or masts are required for a variety of purposes, such as supports for solar arrays, as antennas, or to locate experiments remote from the spacecraft environment. There is a continual desire in the space community to build increasingly larger structures for space exploration and for the collection or reflection of electromagnetic waves of varying wavelength. In order to achieve these goals, it is necessary to have lower mass structures with better launch vehicle packaging efficiency. Large deployable structures are considered to be an integral part of the development of large reflectors, Earth observation antennas, radiators, sun shields and solar arrays. The problems associated with deployment of large structures in space have been addressed through mechanical deployment systems such as deployable trusses and Storable Tubular Extendable Member (STEM) booms (Figure 1).

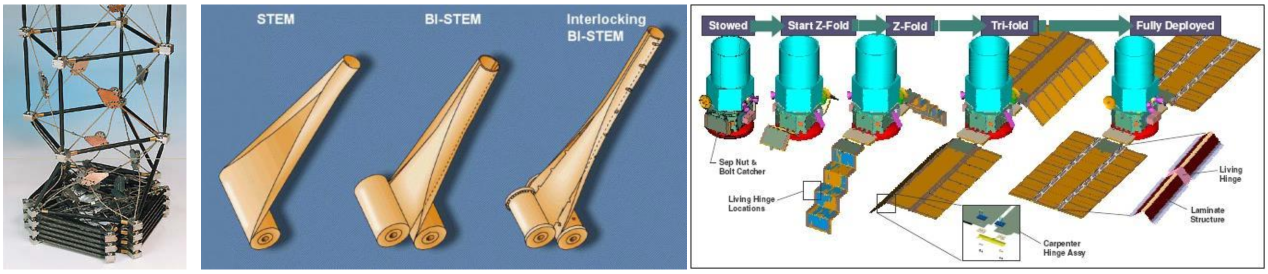

Figure 1 – From left to right examples of a deployable truss structure, STEM booms and solar array deployment of Fold Integrated Thin-Film Stiffener (FITS) mechanism

There are three phases in the design case of all mechanical deployment systems: Launch - The stored configuration must survive this phase; Deployment - Pre-flight testing is difficult because it is performed in 1 g, and gravity offload Mechanical Ground Support Equipment (MGSE) is relatively crude; Deployed operation - Subsequent to the disturbance forces experienced during deployment, the structure can be relatively flimsy.

The manufacture of structures in-orbit in continuous lengths by pultrusion offers significant benefits over conventional methods - Deployment systems can be simplified, the number of joints can be greatly reduced, the structural mass can be optimised by eliminating the need to withstand launch loads, the deployment system stowed volume can be reduced, and pultrusion raw materials can be transported into orbit at a high packaging density for fabrication of very-low-density structures in-orbit.

The pultrusion process utilises a supply of fibre reinforcement tows stored in an array of reels. The individual tows are threaded through a guide plate that serves to correctly align the tows as they are drawn into the compression section of the Die. If the tows are not pre-impregnated, a resin matrix is injected into the Die. The tows pass through the compression section which consolidates the matrix and fibres together. The curing section of the Die is heated causing the section to cure before it exits the Die. A drive mechanism pulls the section through the machine at a rate such that the dwell time in the Die is sufficient to ensure correct curing of the matrix. The quality of the Pultrudate is often analysed by an ultrasonic Non-Destructive Inspection (NDI) system to ensure that the process parameters are adjusted correctly.

3.0 DESIGN, DEVELOPMENT AND VERIFICATION

Design, development and verification activities to reach flight-ready technology are partially identified through the specification of BB, Engineering Model (EM) and Flight Model (FM), requirements which consider incremental improvements in capability and operating environment (Table 1).

Section	Subsection	BB (TRL 1-4)	EM (TRL 5-6)	FM (TRL 7)
System Architecture	-	Baseline	As per BB	
Function	Pultrusion rate	0.5 mm/s	1.0 mm/s	0.5 mm/s
	Pultrusion quantity	1000 mm (Ambient) 30 mm (Vacuum)	1000 mm (Ambient) 30 mm (Vacuum)	3.0 m (Orbit)
	Operation	>12 Cycles	>12 Cycles	1 Cycle
	Termination	Manual	Automatic	Automatic
	Design safety factor	1	>1.5	>2
	Motorisation factor	1	>1	~5
Physical Properties	Mass	<20 kg (inc. 10% margin)	<20 kg (inc. 10% margin)	<10 kg (inc. 5% margin)
	Size	350 X 350 X 300 mm	N/A	400 X 300 X 300 mm
	Pultrudate properties	N/A	N/A	Specified
Operating environment	-	Laboratory	Aircraft	Low Earth orbit Microgravity -120 to 120 °C Ariane 5 Launch
Mechanical Interfaces	-	N/A	A310 ZERO-G	Spacecraft
Electrical Interfaces	Power consumption	<200 W	Not specified	<200 W (Peak, operational) <2 W (Peak, standby)
Monitor and Control	-	Baseline	As per BB	As per EM
Parts, Materials and Processes	Outgassing	RML <1.0% CVCM <0.10%	As per BB	Compliance (ECSS-Q-ST-70-02C)
	Components	-	High commercial standard Preferred (ECSS-Q-ST-70-71C)	Selection (ECSS-Q-ST-70-71C) Storage life >6 months (ECSS-Q-ST-70-22C) In-orbit > 6 months Thermal cycling (ECSS-Q-ST-70-04C) Radiation (ECSS-Q-ST-70-06C) SCC Resistance (ECSS-Q-ST-70-36C)
	Cleanliness and Contamination	-	Sterilisation (ECSS-Q-ST-70-53C)	Sterilisation (ECSS-Q-ST-70-53C)
Safety	-	Baseline	A310 ZERO-G	Spacecraft
Test	-	Pultrudate	As per BB	-

Table 1 – Design, development and verification

Hard and target BB requirements were identified encompassing System Architecture, Function, Physical Parameters, Operating Environment, Mechanical Interfaces, Electrical Interfaces, Monitoring and Control, Parts, Materials and Processes, Safety and Test. Principal verification methods were Test, Analysis and Review of Design. Subsequent to design and test activities, the BB was found to be compliant with all hard requirements.

The BB used in this activity was developed prior to and independent to this activity. The BB is BIPR therefore details are not included as this Executive Summary Report is not marked 'Proprietary Sensitive'.

The BB Pultrusion Machine comprises a Puller Assembly, Die Assembly, Termination, Tape Feed Assembly and Resin Injection Pump Assembly.

A channel profile was down selected subsequent to a trade study of potential Boom profiles (Figure 2), considering e.g. Die geometry and mechanical properties.

Figure 2 – Candidate Boom profile, Left to right; Flat Bar, Curved Bar, Tube, Channel

Matrix and fibre reinforcement materials were selected subsequent to market assessment. An epoxy resin was specified due to it having a low volatility and toxicity. Epoxy resins are commonly used in space applications as a matrix material and are considered to offer the lowest risk route to space qualification. Other systems considered were phenolics and polyester resins which are readily available and used in commercial pultrusion, but were discounted due to the elevated risk of these compounds not being easily flight-qualifiable. The fibre reinforcement used in space polymer composite systems is generally a form of carbon fibre, although glass fibres are used, generally when RF transparency is a requirement. A pre-woven carbon fibre cloth tape was selected. The use of woven tape simplifies handling of the unconsolidated reinforcement and is representative of the way in which spar sections are laid-up in commercial aerospace applications.

The lay-up selected comprised three layers of (0°/90°) carbon fibre plain weave fabric formed into a 'U' channel. The laminate is designed to be symmetrical about the XZ plane in order to prevent distortion due to differential curing stresses and is balanced to exhibit predictable bending stiffness properties. The resin system selected for use is designed for use in commercial, terrestrial pultrusion processes. The epoxy resin is Hexion 'EPON 826' bisphenol-A resin, mixed with Lindau Chemicals LS-81K curing agent. The compounds are considered to be hazardous and are volatile at processing temperatures.

Space applications will require the free end of the Pultrudate to be equipped with a payload or fitting to allow some functional purpose or connection to other structural elements. In order to provide an appropriate mechanical (and electrical) interface to such systems, a Termination Assembly (Figure 3) serves to gather and retain the free ends of the fibre consumables into an appropriate geometry for the subsequent interface.

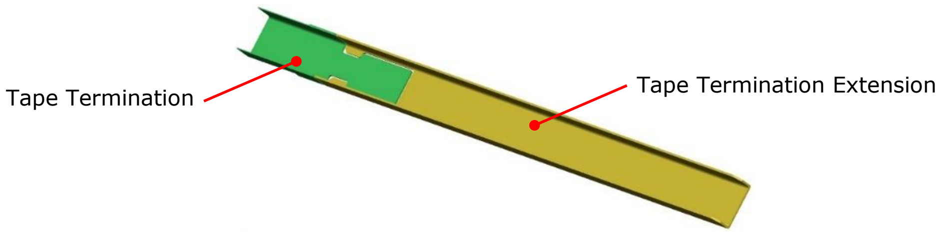

Figure 3 – Termination Assembly

Structural analysis of the BB was conducted for constant acceleration, sinusoidal vibration and random vibration load cases in accordance with ECSS-E-10-03A - Space Engineering – Testing. Constant acceleration: Levels along each axis, both directions 7.5 g. Duration 3 minutes. Sinusoidal vibration: Equipment mass M ≤50 kg, first natural frequency >100 Hz for all axes. Random vibration: Equipment mass M ≤ 50kg. No significant effects were observed. Thermal analysis was conducted to evaluate thermal behaviour of the Die, and subsequently correlated with empirical testing.

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4.0 MANUFACTURE AND TEST

The BB Pultrusion Machine, MGSE and EGSE was refurbished/assembled and commissioned. The test set-up in both ambient and vacuum was established (Figure 4). Optimum pultrusion parameters for the manufacture of composite Booms were derived.

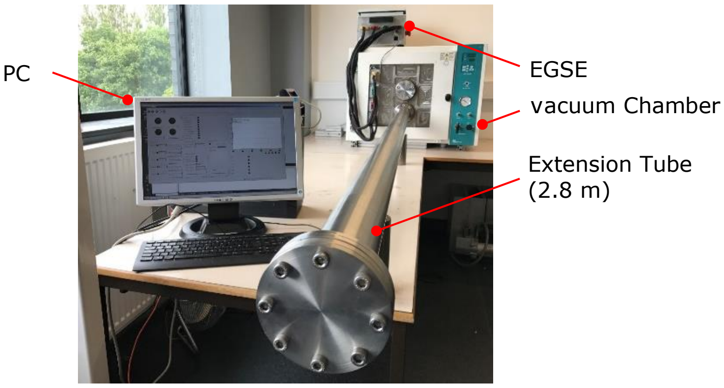

Figure 4 - Manufacture set-up - Vacuum. Pultrusion Machine located within Vacuum Chamber.

Composite tests and corresponding test methods were defined, such that mechanical and material properties, and the variation thereof, could be determined (Table 2).

Test Type	Property of Interest	Test Method
Tensile	Ultimate Tensile Strength (UTS)	ISO 527
	Young's Modulus (YM)	ISO 527
Flexural	Inter Laminar Shear Strength (ILSS)	ISO 14130
	Flexural Modulus (FM)	ISO 14125
Compressive	Ultimate Compressive Strength (UCS)	ASTM D6641
	Compressive Modulus (CM)	ASTM D6641
Porosity	Microsection	-
	Non-Destructive Inspection (NDI)	-
Dilatometry	Coefficient of Thermal Expansion (CTE)	ISO 11359-2
Differential Scanning Calorimetry	Glass transition temperature (Tg)	ISO 11357-1
	Cure energy (ΔH)	ISO 11357-1
	Degree of Cure (Doc)	ISO 11357-1

Table 2 – Tests conducted

The quantity and location of test coupons to be extracted from the Booms was defined (Figure 5, Figure 6). A sample of uncured epoxy resin was employed as a reference for thermal property data. Results obtained are tabulated (Table 3).

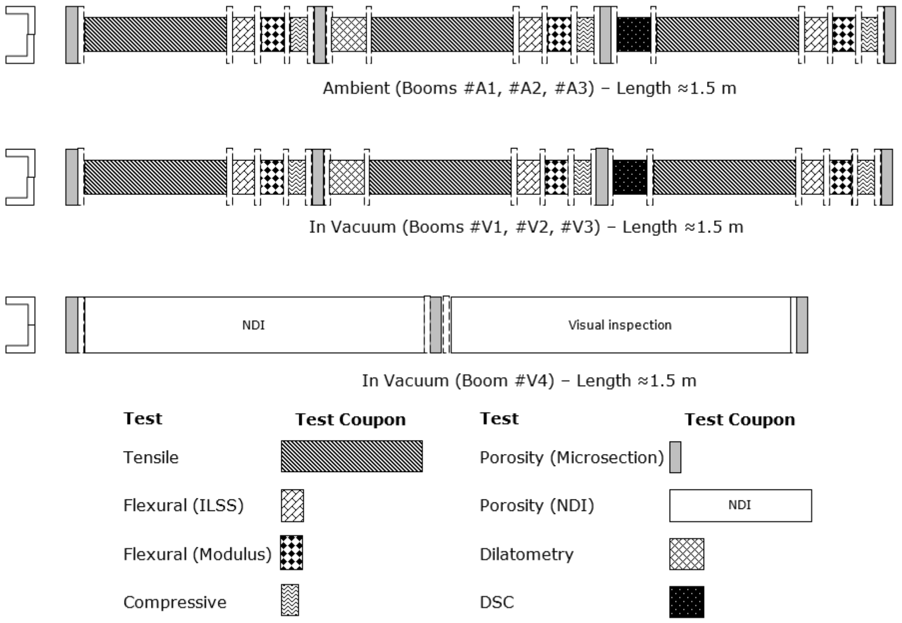

Figure 5 – Pultrudate showing derivation of test coupons

Figure 6 – Section of Pultrudate post manufacture

Parameter	UTS (MPa)	YM (GPa)	ILSS (MPa)	FS (MPa)	FM (GPa)	UCS (MPa)	CM (GPa)	Tg (°C)	ΔH (J/g)	DoC (%)
Ambient										
Min.	619.5	42.3	31.9	282.9	35.0	155.37	40.12	58.76	-23.94	92.54
Mean	738.4	53.9	46.4	533.9	43.0	177.64	42.81	60.33	-21.03	93.45
Max.	942.0	65.4	69.3	813.3	57.5	189.46	47.88	63.10	-17.42	94.57
St. Dev.	95.8	6.0	11.3	206.8	7.5	19.30	4.39	1.98	2.61	0.81
CV (%)	13.0	11.1	24.4	38.7	17.5	10.86	10.26	3.28	-12.40	0.87
Vacuum										
Min.	619.47	46.92	29.8	391.0	34.1	146.89	31.39	58.26	-21.99	96.20
Mean	619.47	46.92	44.2	590.9	40.7	162.40	38.82	59.59	-20.01	96.70
Max.	619.47	46.92	56.6	807.9	52.2	189.18	46.92	61.35	-17.42	97.61
St. Dev.	-	-	11.3	154.2	5.6	13.55	5.58	1.59	2.35	2.35
CV (%)	-	-	25.6	26.1	13.7	8.34	14.39	2.67	-11.74	2.43

Table 3 – Consolidated test data

Tensile: Test data shows relatively good agreement. The Coefficient of Variation (CV) is calculated for UTS (13.0%) and YM (11.1%) showing relatively low variability amongst the sample data. Little variation in the tensile properties of the Pultrudate is expected as these are principally determined by the material properties of the carbon fibres in the pultrusion direction. Variance is likely a result of fibre misalignment or spreading, yielding a variation in the total number of 0° direction fibres in the test samples.

Flexural: Ambient test data shows relatively good agreement. The CV is calculated for ILSS (24.4% to 25.6%) showing relatively high variability amongst the sample data both in vacuum and at ambient pressure. As ILSS is predominantly governed by the inter-ply adhesion the variance in results may be indicative of inconsistencies in the wet-out of fibres or of high shear forces in the resin during the gelation phase.

Flexural Modulus: Ambient and vacuum test data for FS shows a relatively large CV (38.7% and 26.1%), though trends are in approximate agreement, indicating a tendency toward consistency of manufacture. Test data for FM appears to be of a more consistent nature. The flexural properties (FS and FM) are influenced predominantly by the interlaminar tensile strength (arising from the resin) and from the quality of the layup (i.e. fibre straightness).

Compressive: Test data shows relatively good agreement, though it is acknowledged the sample population is small. CV is calculated for CS (10.9%) and CM (10.3%) showing relatively low variability amongst the data for ambient Pultrudate.

Differential Scanning Calorimetry (DSC): The DSC results obtained indicate a slightly higher mean DoC in samples produced in vacuum compared to those in ambient (96.7% vs 93.45%). This is considered most likely to be caused by to the lower rate of heat flow out of the Pultrudate and Puller Assembly structure in vacuum due to the elimination of convection cooling provided by the atmosphere. This effect will cause the Pultrudate to remain above a curing temperature (~100°C) for longer. Thermal control of the die in vacuum required that it be actively cooled by means of a cold plate and cooling loop, therefore the thermal profile within the die was different to that obtained in ambient. The CV seen in the uncured resin ΔH values represents the error/inaccuracies present in the test method, which will be made up from contributions arising from error in sample measurement, error in the DSC measurements and variations between samples (chemical activity etc.).

Glass transition temperature CV values (3.28% and 2.67% in ambient and vacuum conditions respectively) demonstrate consistency in the properties of the cured material that indicates that the cure cycle of the pultrusion machine operates in a consistent and predictable manner.

5.0 CONCLUSIONS

In order to obtain an indication of the mission scenarios where pultruded boom deployment systems offer improved performance or efficiency over state-of-the-art systems, performance metrics have been selected which allow for comparisons to be made. Several boom deployment systems with flight heritage are compared to data extrapolated from a previous MPL study involving a BB Pultrusion Machine. The BB and Pultrudate were not designed for flight or for a particular mission scenario, therefore the performance comparisons made may be considered to be indicative of performance achievable in such scenarios.

The specific mass is plotted versus the boom length for several state-of-the-art boom deployment mechanisms as well as the BB Pultrusion Machine (Figure 7). The location of the BB curve indicates that pultruded booms will be competitive with existing systems at lengths over ~100m.

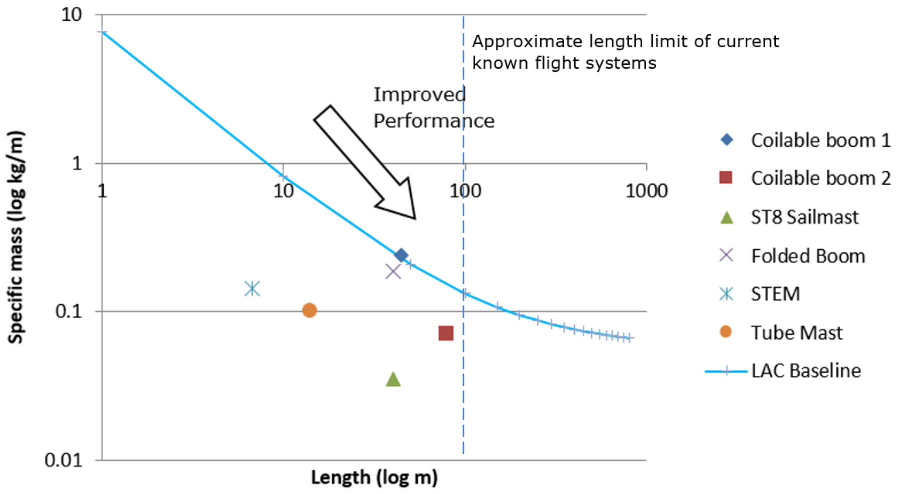

Figure 7 – Deployed length versus specific mass

Technology limitations identified in the present project include Pultrudate property variation: The CV noted in the flexural properties of the produced Pultrudate is high in comparison to the CV in both DoC and in tensile and compressive properties. The compressive and flexural properties are greatly influenced by the layup quality (e.g. fibre alignment) and the wet-out of the fibres. The results therefore suggest that the main source of Pultrudate quality variation arises from the misalignment of fibres during pultrusion. Further work will be required to investigate the fibre feed and guiding aspects of the pultrusion process in order to eliminate this source of variance.

Testing on composite booms produced in vacuum conditions by means of pultrusion indicate that the current BB system produces composite material with a variance in properties approaching that of commercially-manufactured composite aero-structures. In a commercial environment, a CV in the 4% to 10% range is typical of composite materials and would yield adequate conservatism in engineering practice. Thus, whilst the mechanical properties obtained within the present test are not of direct interest, the variation of those properties (tensile, compressive) compares well to that typically expected of industrial manufacturing processes for composites used in aerospace primary structures.

The roadmap to flight which shows historic, current and future development is depicted (Figure 36). The present phase of the study (Phase 1B) may be considered to have achieved TRL 3. The MPL in-space manufacturing technology, within the context of the General Support Technology Programme (GSTP) activity (Phase 1B) has achieved TRL 3. External to the present GSTP activity the technology has been developed to TRL 4, additionally a LuxImpulse activity is in place to extend this to TRL 6 by Quarter 4 (Q4) 2018 at a cost of €2.5 m, which includes the development of the first application (a radio transmission interferometry/geolocation mission, §6.4). The LuxImpulse activity and further exploitation of the MPL in-space manufacturing Intellectual Property (IP) is achieved through its mission-dedicated Luxembourg-based daughter company, Kleos Space S.a.r.l.

Flight qualification for the technology is currently planned to be achieved through deployment on the first satellite of the radio transmission interferometry/geolocation mission at an estimated cost of €8.0 m, funded commercially and launched ~Q4 2019.

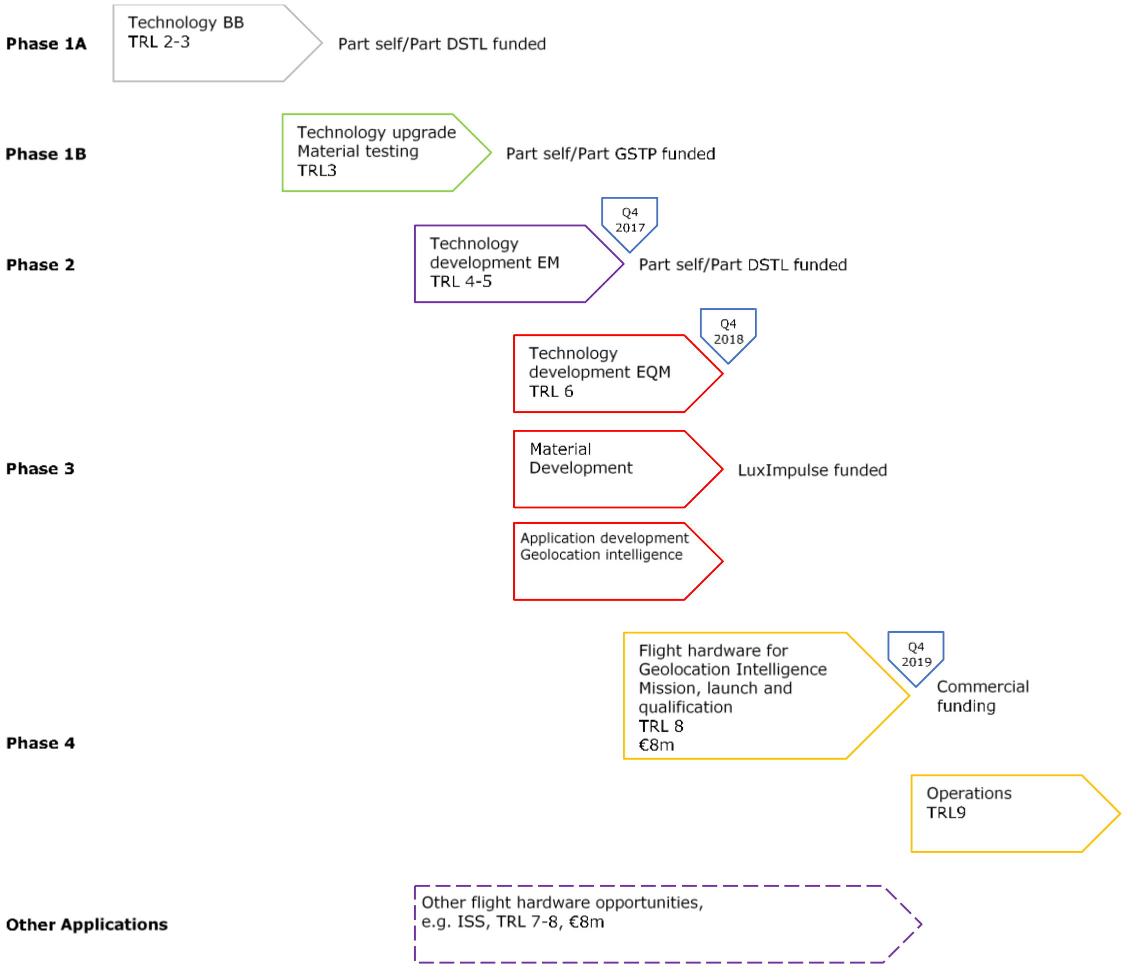

Figure 8 – Roadmap

Exploitation areas previously identified employ pultrusion technology in a similar manner; to serve as a deployable structural member with which to position a receiving device (e.g. antenna) at a specific location, such that an in-orbit array of antennas is established - at separation distances far greater than could be achieved by conventional deployer technology. Deployment of receivers and/or transmitters on the ends of pultruded booms is conceptually straightforward, in that the payload can be attached on the ground as part of the initialisation of the Pultrusion Machine.

Assuming a mission scenario in which a series of Pultrusion Machines are arranged on a single satellite such that booms are produced symmetrically in opposite directions; the exploitation opportunities require minimum pultruded booms of length 15 m for Radar Application or 50 m for Passive Radio Reception (i.e. interferometric geolocation of specific transmission types such as Global Positioning System jammers, Automatic Identification System beacons and mobile telephony). Pultruded composite booms of length ≈2 m have been manufactured in the present project, and in previous work by MPL ≈5 m. Whilst the project was not intended to determine the performance and ultimate length achievable, the data obtained suggests that, on completion/resolution of performance limitations previously discussed, boom lengths of the order of magnitude for Passive Radio Reception applications are certainly achievable, thus reinforcing the potential route for the technology.