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Advantages and capabilities of precursor missions on CubeSats in preparation of commercialization and large-scale missions

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Abstract

Large-scale satellite missions, that expand technological capabilities significantly, usually need long development times and high amounts of funding while they balance high reliability and the risk of unproven technologies. Small satellite missions, on the other hand, are limited in their capabilities and area of application, but provide a quick and affordable access to space.

Many large-scale missions have very ambitious technical goals resulting in challenges and unforeseen circumstances during the development. This combination leads to an increased risk, cost and time. Especially the timeline is crucial if missions want to claim a new field. While CubeSats can't replace larger satellites due to the limited performance relating to their size (e.g. power generation and dissipation or payload capacity), they can be a huge enhancement when they are understood as precursor missions to large-scale and commercialization programs. The precursor can be used to de-risk the main mission and help it meet its development timeline by reducing the scope of the precursor to key challenges that are already understood when the main mission starts.

The German Aerospace Center (DLR) successfully demonstrated their in-house developed OSIRIS4CubeSat/ CubeLCT, the world's smallest commercial laser communication terminal, on-board a 3U CubeSat to de-risk the parallel industrial application of the terminal via its industrialization partner Tesat Spacecom. The upcoming mission CAPTn-1, a 12U CubeSat, is following the same approach, while incorporating four different technological systems in a single mission that all were developed by DLR: The reliable and high-performance On-Board Computer ScOSA, DLReps, an intelligent satellite battery with an integrated health monitoring, a Generic Software-Defined Radio as well as a smart retroreflector enabling positioning and identification via satellite laser ranging. Currently, CAPTn-2 is under preparation to continue regular in-orbit validation possibilities for DLR technologies. This approach is also demonstrated by the German Space Agency's Small Satellite Initiative project, which will launch six novel subsystems on three CubeSats. Launching miniaturised systems for in-orbit demonstration as a proof of concept and potentially as a minimum viable product has proven to be a driver of innovation.

The paper describes DLR's approach to use CubeSat precursor missions to de-risk the timeline of large-scale and commercialization missions by solving and demonstrating key technology challenges before the main mission starts based on the successful industry-funded mission PIXL-1 and the upcoming institutionally funded CAPTn-mission.
Keywords: CubeSat, NewSpace, Space research, Precursor mission, In-Orbit Demonstration

1. Introduction

Large-scale scientific space missions, such as the James Webb Space Telescope (JWST) or other comparable missions provide an enormous potential for the exploration of space, live on Earth and everything in between. In many cases, these missions are carried out in international collaborations, since one nation can neither afford such a mission nor has the required knowledge in all aspects. These missions can have long durations of 15 and more years with a large round of stakeholders involved.

This leads on the one hand to a very powerful projects with international collaboration, ambitious goals and outstanding results. On the other hand, these large-scale missions often face delays and financial risks during the runtime. Especially technical challenges during the development, driven by changing requirements from a large consortium or unforeseen technical issues shift the timeline and increase the costs. The development of the JWST as an example started in 1996 as a collaboration between NASA, ESA and CSA and was supposed to launch in 2007 for a total budget of around $3.3 billion. Technical challenges during the development shifted the launch to December 2021 with a total budget of roughly $9.7 billion [1]. But not only missions like the JWST, the most expensive development of unmanned space flight, suffer from delays due to technical challenges.

At the same time, long project duration and high financial risks are inversely proportional to the acceptable risk of the mission. The combination of long project duration, high cost and low risk limit the scientific potential and innovation of the mission and requires "Classical Space" approaches with a huge overhead for documentation, reviews, qualification and processes. This limits the opportunities of demonstrating new technologies and claims in scientific fields and can lead to use technologies and components which are not state-of-the-art.

"NewSpace" approaches come with the promise of a quick access to space due to reduced overhead and higher accepted risks. The "time to orbit" is usually shorter and allows to claim new fields and gather experience from new key-technologies in space that would not be possible in a large-scale mission. Since the cost is usually lower and the mission purpose more focussed, also the consortium can be smaller, more agile and innovative. At this point, "NewSpace" is not to be understood as "gambling and hoping for the best", but as the conscious decision to move effort from simulation, processes and documentation into the fast development of hardware and testing with the acceptance of additional iterations.

SpaceX is one of the examples that demonstrated an iterative, agile approach to engineering and project management, prioritizing rapid prototyping, continuous testing and a high level of vertical integration "in-house" – "They don't spend forever trying to get each version perfect, which would be very expensive. Instead, they build what their design says, rapidly and without being too careful. They want to get the thing to the test stand, even if it has imperfections" [2,8].

"Classical Space" and "NewSpace" should not be understood as the opposite but as a perfect combination to demonstrate new technologies in orbit fast and pave the way for a large-scale mission with reduced technical risks, reduces timeline and a lower financial risk.

This paper will give an overview of the German Aerospace Center's (DLR) strategy of de-risking large-scale missions and technology transfer with precursor missions and will show two concrete examples with the development of the smallest laser communication terminal worldwide and the technology transfer to an industrial partner as well as the mission CAPTn-1 with the demonstration of newly developed key components. The paper will be completed by the view of the German Space Agency within DLR as well as a discussion and outlook.

2. De-risking the main mission: precursor missions

Precursor missions, especially on basis of CubeSats, have multiple benefits. The flexible and modular design of standardized CubeSats enable modular payloads and easy integration of new technologies, supporting rapid payload prototyping. Furthermore, CubeSats allow the demonstration of multi-satellite coordination, networking, and distributed sensing concepts which is also key for future applications and In-Orbit Demonstrations (IOD) and In-Orbit Verification (IOV).

One of the underlying challenges of large-scale missions is a large consortium with a huge number of (and sometimes even changing) requirements, that complicate the technical solutions especially during the development. Such projects generate new insights and knowledge during the development process which can have an influence on the project's scope and development itself. This can lead to changing requirements and deviations from the original project plan. Such changes during the project can be very resource intensive, increase the costs and delay the mission. With potential end customers involved, the project needs to cover a broad range from technological innovation, technology demonstration as well as operational use cases for a customer.

Throughout large-scale space missions, the main challenges have been identified to be:

- Low level of acceptable risks, hence a lower level of innovation
- increasing costs due to technical risks during development
- increasing complexity of the technical solution
- large consortiums that complicate decision making and alignment within the project
- long mission durations

Besides the challenges that are listed above, large-scale missions also come with huge benefits:

- Huge impact like the Hubble-telescope, JWST or the landing on the Moon
- Funding that one single nation could not provide
- High level of confidence due to intense simulation and documentation

To overcome the drawbacks of large-scale missions, DLR investigated to combine the advantages of large-scale mission with small-scale precursor missions in a staged approach. Precursor missions can provide a huge benefit to the following (or parallel) large-scale mission if they ensure:

- Quick access to space to demonstrate new technologies and claim scientific successes
- Reduction of the mission scope to the minimum to demonstrate the key technology or feature
- Results of the precursor mission during the development phase of the large-scale mission to benefit from the experience and reduce technical risks
- Lowering the barriers of space access: Universities, start-ups, countries without established space programs and organizations can easily participate in space missions which

helps fostering innovation and broadening the space ecosystem

To achieve the above-mentioned goals, we believe precursor missions should target the following goals:

- Focus only on one key technology as a subset of the large-scale mission scope. Focus on bringing this technology to space
- Limit the consortium to the minimum to remain agile in development and decisions
- Prepare a detailed risk management to balance chances and risks on the way to space
- Change early from simulation to hardware and learn in the lab (and prepare the hardware with additional measurement points, detailed telemetry and sensors to allow a detailed analysis)

By understanding precursor missions as an early part of large-scale missions, the advantages of both worlds – Classical and NewSpace – can be combined.

3. De-risking science missions

The following sections show two examples of DLR missions of the last years that used the concept of precursor missions as a measure of de-risking. OSIRIS4CubeSat was a development by DLR's Institute of Communications and Navigation (DLR-KN) and demonstrated a highly compact system design for a laser communication terminal, especially suited for CubeSats. The development always aimed for a technology transfer to an industrial partner to bring the technology to market. The result is known as CubeLCT and is currently the smallest, commercially available laser communication terminal worldwide.

CAPTn-1 is a DLR mission to demonstrate new technologies in space. The Cubesat to Accomodate Payloads and Technology Experiments (CAPTn-1) hosts different newly developed payloads like an on-board computer, batteries, retro reflector and an ADS-B receiver.

3.1 From OSIRIS4CubeSat to CubeLCT and beyond

Free space optical communications (FSOC) can replace or extend classical radio-frequency (RF) channels in many different use cases and missions. DLR does not only do the fundamental research in laser communication but also develops optical communication terminals with a focus to serve potential market needs. Therefore, DLR works together with strong industry partners. The OSIRIS4CubeSat project was a close collaboration between Tesat Spacecom GmbH&Co KG and DLR-KN. The mission was fully funded by Tesat. DLR-KN's goals were to develop a laser communication terminal, especially designed for CubeSats and to demonstrate FSOC feasibilities in a relevant scenario. This prepared the technology for the product market entry done by Tesat.

From commercial perspective, it would be ideal if a laser communication terminal (LCT) comes with the same product-market fit as classical communication systems and can serve the same scenarios. This would mean, it had to fulfil (among others) the following requirements:

R1	Very high data rates
R2	Bidirectional data transmission
R3	Direct-to-Earth (DTE) and inter-satellite communication (ISL)
R4	Inter- and intraplane communication
R5	Communication and operation of the satellite in parallel
R6	Own data handling
R7	Full standardization

Developing an LCT which fulfils all these requirements from scratch would have been an extremely high effort and contained a lot of risks. Such a system would be highly complex so that all single subsystems had to be developed, tested and qualified within one project. Ensuring that everything works together in space flawlessly, without knowing how the single technologies behave in space, would be very risky and would generate a huge effort for testing and qualification in advance. This increases the project resources significantly.

Figure 1: CubeLCT as a product (Credit: Tesat Spacecom)

Thus, DLR-KN followed, in line with Tesat, the precursor approach. The idea was to demonstrate isolated functionalities of an LCT in-orbit to gain knowledge from the final environment. Reducing the functionalities to a reasonable base allowed a development and demonstration within a very short timeframe, compared to high-complex LCTs that cover all customer needs.

OSIRIS4CubeSat is an LCT that demonstrated an end-to-end transmission over an optical DTE for the first time in orbit [3]. Even though it did not cover all possible scenarios RF can serve, it proofed the usability of laser communication in the final environment. This achievement on the one hand gained trust in the technology of FSOC on CubeSats and marked the path towards a commercial product for Tesat (Figure 1). On the other hand, the experiences and gained knowledges of the project helped DLR-KN to improve this technology and adapt their processes for upcoming developments and missions.

A modular design with distinguishable subsystems was considered from the beginning and standard interfaces allowed simple adaptions and extensions for future developments. The insights and gained knowledges from the precursor mission could directly be transferred into the successor mission CubeISL. In this development, the terminal's capabilities were extended from pure Direct-to-Earth (DTE) communication towards DTE and Inter-Satellite-Link (ISL) data transfer [4]. The reuse of nearly the entire concept of OSIRIS4CubeSat allowed a significant reduction of test and qualification effort and enabled short development times with a relative low mission risk.

The CubeISL IOD-mission will demonstrate an optical ISL with 100 Mbps and increase the data rate in the DTE to 1 Gbps [5]. Furthermore, CubeISL is equipped with its own data handling unit (DHU) as another step towards serving the market needs. As a lesson learned from the previous project, IKN included Tesat very early in the project. This allowed Tesat to adapt IKNs integration procedures into their mass manufacturing processes. This will allow DLR to demonstrate the LCT in a very early stage, while Tesat can focus on the serial production of a fully standardized LCT, the scalable optical terminal with 20 mm aperture (SCOT20).

Figure 2: Evolution from OSIRIS4CubeSat to Cube1G

The next step for IKN and Tesat was being independent from the satellite's attitude. The modular approach allowed extensions with a coarse pointing assembly (CPA). Such a gimble mechanism can steer the laser beam around azimuth and elevation axis and describe the whole hemisphere. Both CubeISL and SCOT20 allow simple extensions with a CPA to provide further functionalities and serve the market's needs. Figure 2 shows the three development steps of DLR's LCTs for CubeSats.

The picture shows how the LCT evolved. The terminal design of OSIRIS4CubeSat can be found nearly unchanged in the middle layer of CubeISL. The left part of Cube1G shows the CPA with the prism to steer the laser beam.

With regard to the requirements defined in the beginning of this section, the terminals can fulfil the ones respectively depicted in Table 1.

Table 1. Requirement compliance of the three LCTs for CubeSats developed by DLR

Requirement	OSIRIS4CubeSat	CubeISL	Cube1G
R1	Partly	Yes	Yes
R2	No	Yes	Yes
R3	No	Yes	Yes
R4	No	No	Yes
R5	No	No	Yes
R6	No	Yes	Yes
R7	No	No	No

The table shows that the staged approach increased the functionalities in every development level. Tesat took over the technology and enabled the last requirement defined in this work, the communication standardization for the placement in a commercial market.

The transition from OSIRIS4CubeSat to Cube1G distributed the development risks and uncertainties over several projects. Developing a complex system like Cube1G from scratch would have accumulated all appearing setbacks and obstacles in one project path. This would have led to unforeseen delays and exceeded initial resource and time planning by far. The staged approach allowed to mitigate these unknowns and, in the overall timeline, reduce the project time.

Furthermore, the lessons learned and insights of the precursor missions could directly be transferred into the development of the successor missions. Adjusting technical properties of the reused subsystems, based on the insights of the behaviour in space, will improve the performance of the following missions.

The modular approach also enabled to reuse known processes and reduce cost and effort. Successor projects benefit from already qualified systems and reduce time and cost for testing and qualification [6].

3.2 Technology demonstration in space with CAPTn-1

The CAPTn-1 (**C**ubesat to **A**ccomodate **P**ayloads and **T**echnology Experime**n**ts) missions aims to demonstrate new technologies in a low Earth orbit. The advantage of the program is the demonstration of several payloads without the need to launch several independent CubeSats. This reduces costs, saves time and reduces debris. CAPTn-1 is based on a 12U-CubeSat which accommodates the following payloads:

Mission Name	Description
ScOSA	The ScOSA (Scalable On-board computing for Space Avionics) payload will demonstrate the feasibility of a heterogenous and distributed on-board computer. The ScOSA architecture combines high-performance COTS (Commercial-Off-The-Shelf) components, including algorithms in FPGAs (Field-Programmable Gate Arrays), with a radiation-tolerant reliable computing node.
DLReps	The engineering approach of DLReps is to design a modular and scalable system that consists mainly of COTS (commercial of the shelf) components and intelligent ICs that help to manage and monitor the cells. The battery of the DLReps project shall be flexible in possible size, power and with interfaces to form an experimental power system that interfaces to a battery system, PCDU, solar panel and a consumer.
RetroReflector	The payload consists of two retroreflector-arrays in the shape of pyramids that will be used for satellite laser ranging experiments.
GSDR	In this experiment, the feasibility of a multi-channel ADS-B (space-based Automatic Dependent Surveillance Broadcast) reception system on a CubeSat is to be tested. The system is based on an already developed radio platform (GSDR) and three developed ADS-B antennas.

The mission is based on a 12U-CubeSat, which will be procured in the project. This allows to focus the development efforts on the payloads and not in the satellite platform which is no longer a scientific endeavor. With the hosted payloads, the satellite will reach a mass of roughly 20kg.

The main goal of the CAPTn-1 mission is the demonstration of new technologies that have never been tested in space. The payloads have been qualified for the use in a Low Earth Orbit on ground but with the limitation of a maximum Technology Readiness Level (TRL) of 6. To further increase the TRL, a demonstration in space is required. As described in section 3.1, DLR aims to transfer developed technologies under a license agreement to the industry after successful demonstration. Therefore, it is key to reduce the mission scope to ensure a quick access to space, an early claim of new technologies being demonstrated as well as a seamless handover to serial manufacturing.

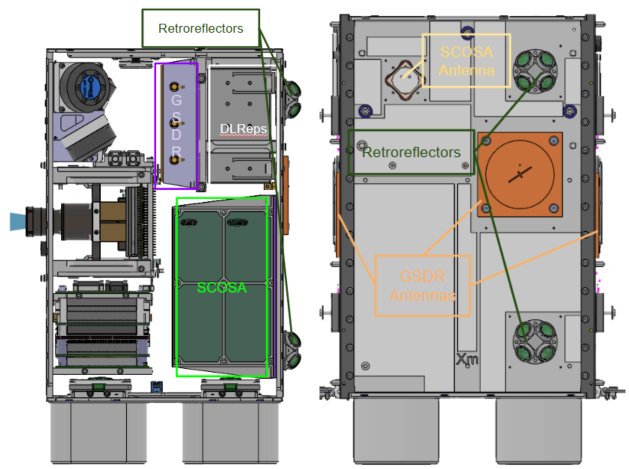

Figure 3: Space segment with integrated payloads from CAPTn-1

The launch of CAPTn-1 is currently planned for 2026. In parallel, the successor mission CAPTn-2 is already under preparation to allow more payloads to be demonstrated in space.

4. Relevance for the German Space Agency

The German Space Agency at DLR undertakes statutory tasks in the space sector on behalf of the German Federal Government. In the dynamic landscape of space technology, the German government has launched the "Small Satellite Initiative" as part of the new Germany Space Strategy released in 2023, with a precursor in 2022. This initiative marks a significant milestone and dedication in Germany's small satellite activities. The German Space Agency is driving forward the Small Satellite Initiative to pave the way for a complete relevant value chain in Germany. German industries are supported to achieve a good competitive position in this market, especially with regard to the development of innovative technologies and services, at SMEs and start-ups. Research institutions and universities will also be considered in their role as innovation drivers and incubators for NewSpace approaches.

To achieve these strategic goals, the German Space Agency has defined five measures to be addressed:

1) Research and development of small satellite technologies
2) Organize and conduct competitions for small satellite platforms development, in-orbit-demonstrations of new technologies and mission opportunities for scientific payloads
3) Incentivize cross-industry modern production concepts and processes, automation technologies and production robotics to be transferred to enable adaptive series production of small satellites
4) Engage in anchor customer business for governmental demands that can be covered by small satellites
5) Management and support activities, technical consulting of small businesses and startups as well as organization of conferences

Aimed at measure 2) for example the German Space Agency launched the Small Satellite Competition in July 2023. The aim of that competition is to provide companies, universities and research institutes a small satellite - including their payload - the opportunity to launch it on a European microlauncher free of charge. Five organisations have been selected with a total of 21 satellites.

Additionally, the German Space Agency launched a second competition in August 2023 called the Small Satellite Payload competition. The winners of that competition had the opportunity to receive a commercially available small satellite platform for their payload, as well as a launch opportunity on a European microlauncher. Seven organisations have been selected with a total of eight payloads to be launched on four small satellite platforms. The following table shows an overview of the technologies as payloads, to be demonstrated in orbit as part of this activity:

Mission Name	Description
START-1	Technology demonstration of a new commercial Hall Effect Thruster (HET) and CubeSat drag sail.
START-2	Technology demonstration of two new chemical propulsion systems using novel green propellants as well as an electric propulsion system using iodine based on High Efficiency Multistage Plasma (HEMP) technology.
CispaSat	Technology demonstration of a cybersecurity subsystem to prevent hackers from taking unwanted control of the satellite.
AICP-Cube	First-time testing of bi-directional data communication for Internet of Things applications in species and nature conservation, based on the mioty communication protocol in low Earth orbit (LEO) as well as demonstration of a LEO-PNT technology in orbit.

These projects emphasize the importance of dedicated small satellites solely for technology demonstration purposes to drive innovation. In the next steps larger systems can be derived from the experience of the in-orbit demonstrations.

This opens new opportunities with the potential of conducting small satellite missions as a precursor or technology pre-development for larger satellite missions. For example, one of the large-scale missions of the German Space Agency is the telecommunication satellite Heinrich Hertz in geostationary orbit. The satellite with a mass of 3.45t was launched on July 5th 2023 on an Ariane 5 with a designed lifetime of 15 years. It features a hybrid propulsion system: one chemical propulsion to raise the satellite from the geostationary transfer orbit to the geostationary orbit as well as two sets of electric propulsion systems for north/south stationkeeping. One of electric propulsion sets is the flight proven SPT-100 HET from the Russian company OKB Fakel while the other set of thrusters is the HEMPT 3050 manufactured by Thales Deutschland. The HEMPT 3050 is an electric propulsion system based on the new technology HEMP which promises higher efficiency and longer lifetime compared to HET. Its development, extensive testing and qualification for Heinrich Hertz was contracted separately by the German Space Agency in 2008. The IOD of this new technology is one of the secondary objectives of the mission. Provided the HEMP low technology readiness level, the HET were added to the mission as a backup electric propulsion system in case the primary option HEMP thrusters failed. As the electric propulsion systems are indispensable for the mission, the risk mitigation measure of adding a secondary electric propulsion system were costly and required additional engineering effort [7].

This example shows the potential for an IOD / IOV mission utilizing small satellites for low-cost technology demonstration, as precursor. The mission Heinrich Hertz was dependent on a new technology and the risk mitigation strategy was to add a redundant system at a significant cost. A miniaturized version of the HEMP thruster could have been launched on a small satellite to demonstrate its functionality, viability and understand its working principles as well as environmental effects on the spacecraft. Depending on the success of the precursor mission, the HET on Heinrich Hertz could have been avoided, significantly reducing the cost of the mission as well as development and qualification efforts on part of the HEMPT 3050 development.

5. Conclusion

Precursor missions, understood as technology demonstration and de-risking for large-scale missions, can provide a large benefit and reduced risks for timeline and finances. Based on the findings of this paper, precursor missions should be included in each large-scale mission from the beginning of the mission to streamline the development and help to remain in the time and financial frame.

The demonstration of OSIRIS4CubeSat/CubeLCT prior to a technology transfer, the demonstration of selected key payloads in the CAPTn-1 mission as well as the example of a de-risking of Heinrich Hertz mission by validating the HEMPFT thruster in a dedicated precursor mission show the potential of including this idea in the mission planning early enough to achieve the maximum output.

As mission concepts increase in complexity (e.g. satellite communication constellations, LEO-PNT) and small satellite missions as well as launch opportunities are decreasing in cost, the concept of conducting precursor missions becomes a potential standard approach to reduce risk for critical components as well as development cost for large-scale missions.

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