OVERVIEW OF THE DLR HIGH ALTITUDE PLATFORM AND SCIENTIFIC POTENTIAL OF THE TECHNOLOGY DEMONSTRATOR HAP-ALPHA

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Abstract

Since 2018, the ongoing high altitude platform project “HAP-alpha” of the German Aerospace Center (DLR) combines the domains of aerospace and space into one single research and engineering project. 16 DLR institutes and facilities under the lead of the Institute of Flight Systems combine their expertise to realize the HAP-alpha high altitude platform. With this project the DLR aims for the following four main research goals in terms of solar powered, unmanned high altitude platforms: 1) The development of novel system concepts and technologies for the realization of robust and cost-efficient high altitude solar platforms. 2) Development and testing of high performance, light weight sensor systems for earth observation. 3) Development of operational strategies and mission scenarios to demonstrate the performance of high altitude solar platforms. 4) Demonstration and flight testing of novel technologies, processes and sensor systems under real environmental conditions

All of them lead to the design and build of a solar powered high altitude technology demonstrator, called HAP-alpha. The HAP-alpha with its wing span of 27 meters, its weight of 136 kilograms and a payload capacity of 5 kilograms is designed as a fully functional high altitude platform to potentially reach the lower stratosphere at around 20 kilometers.

After a brief summary of the History of unmanned solar electric high altitude platforms, the paper gives an overview of the HAP-alpha system. Additionally, the paper will focus on the systems engineering methods we used to set up such a complex aircraft within the research institution DLR. The paper closes with a discussion on the potential of a solar electric high altitude platform, such as the HAP-alpha and what it offers for lower stratosphere scientific experiments.

1. Introduction

The history of unmanned solar powered aircraft that are able to reach the stratosphere and perform long endurance flights goes back to the 1970th. In 1974, Sunrise I, a solar powered aircraft with a wing span of 10 m had its maiden flight. It was designed to climb up to 22 km and to glide down to 3 km at night and stay there, powered by batteries. However, the Sunrise I was destroyed by atmospheric conditions near a cumulus cloud during flight tests. In the 1980th, the NASA started the Pathfinder Program to enable fully solar powered flights, that could last for days. Soon, NASA realized that the available technology was not ready yet and put the Program on hold until the 1990th. NASA reached their first important mile stone in 1997, where the unmanned Pathfinder reached an altitude of 21.802 m, setting up a world record for solar powered aircraft as well as propeller aircraft [1]. Until the early 2000th, NASA refined their Pathfinder and ultimately developed the Helios. The unmanned Helios had a wing span of 74 m and a mass of 929 kg. This enormous, yet very light, aircraft set up another world record in 2001 for reaching an altitude of 29 km. In 2003, the Helios showed the first solar powered flight over more than 24 hours, but was destroyed by atmospheric turbulences shortly after [2]. After this setback, even if it was partly successful, NASA cancelled the concept. In recent years multiple manufacturers and companies developed their own unmanned solar powered high altitude, long endurance platforms and in this way enabled the category of the so-called **High Altitude Platforms** or **HAP**. The most successful until now, among companies such as Boeing [3], Google [4], Facebook [5] and others, is Airbus with their Zephyr program [6]. In its latest installment, the Zephyr-8, with 23 m wingspan 100 kg mass, reached 64 days non-stop flight before it was finally destroyed due to unknown reasons [7]. However, Airbus and the Zephyr set up a new world record and a benchmark for unmanned, solar powered long endurance flights.

But how does it come, that multiple companies and even research institutes around the world invest an enormous amount of money and years of research for this new category of aircraft?

Once operable, a HAP might be an interesting alternative for the use of satellites in the field of communication and earth observation. Compared to satellites the concept of a HAP offers several advantages to its counterpart in space. The HAP can stay over a certain area like geostationary satellites, but is much closer to the surface, providing much better resolution for earth observation applications. At the same time, they can stay over that area for what ever duration might be necessary enabling a continuous observation, unlike non-geostationary satellites which induce an observation delay even if multiple ones are deployed. The other main advantages are, that HAPs are expected to be cheaper to build and maintain and at their end of mission or even end of life, they can be landed and don’t have to end as space debris like most satellites.

2. Environmental and technological challenges

While motivation for the run at high altitude platforms seems to be clear, why are companies still struggling to get a HAP operable. For instance, even the advanced Zephyr Program had several losses of their HAP, even in the last few years [7] [8]. Other companies such as Facebook went as far as

quitting their efforts completely [5]. One answer to that can be found in the challenging environmental and boundary conditions.
First of all, the available solar energy for continuous flight is very limited. That counts even more when considering, that the solar irradiance must be perpendicular to the platform's solar panels. The maximum overall available solar radiation is 1367 W/m² and is strongly dependent on the latitude, day of the year and time of the day [9].
With a simple equation, derived from the basic flight physics equations for calculating lift, drag and electrical propulsion the electrical power for a heavier than air platform can be estimated:

$$p_{el} = \frac{P_{el}}{S_{ref}} = \frac{1}{\eta_{el} * \eta_{prop}} * \sqrt{\frac{2}{\rho}} * \left(\frac{m_{ac}}{S_{ref}}\right)^{\frac{3}{2}} * g^{\frac{3}{2}} * \left(\frac{C_{D0}}{C_L^{\frac{3}{2}}} + \frac{1}{\sqrt{C_L}\pi\Lambda e}\right)$$

In this equation is P_{el} the electrical power, S_{ref} the reference wing area, η_{el} the electrical efficiency including efficiency of solar cells and batteries, η_{prop} the efficiency of the propeller, ρ the density, m_{ac} the mass of the aircraft, g the gravitational constant, C_{D0} the zero drag coefficient, C_L the coefficient for lift, Λ the wing stretch and e the span efficiency factor.
Two main findings arise from the equation above. First, the necessary electrical power raises over proportionally with the aircraft mass relative to the wing area.

$$p_{el} \sim \left(\frac{m_{ac}}{S_{ref}}\right)^{\frac{3}{2}}$$

However, the available wing area impacts the aircraft mass itself, so the dependency boils down to the aircraft mass.
Second, when all the constants are changed to values achieved state of the art technology and considering the available solar radiation perpendicular to the aircraft, one can estimate that the mass related to the wing span, the so-called wing loading, must be less than 6 kg/m² for persistent flights over most of the year [10].

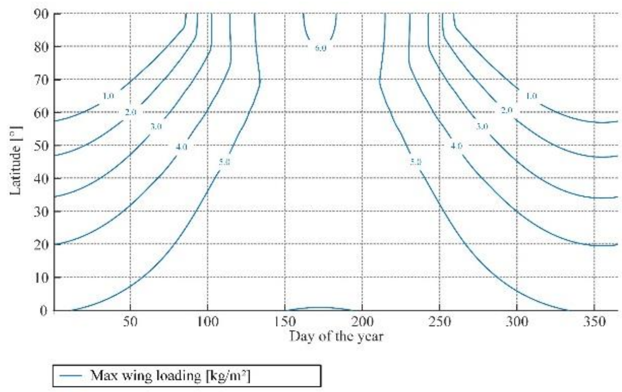

Figure 1: Maximum wing loading for persistent flight

In conclusion, when aiming for solar powered long endurance flights, a HAP must be built extremely lightweight.

Now, the other challenge are the environmental conditions. In the lower stratosphere at around 20 km, the HAP has to face very cold temperatures of -60°C and below at night. This are temperatures, where battery and electronics struggle and need additional heating or protection. However, at daytime and under the bright sun, local temperatures inside the HAP can reach well over 40°C making simple temperature protection insufficient and cooling necessary. Heating at night on the other hand is problematic considering the limited amount of electrical energy stored in the batteries. This makes a clever temperature management essential. In addition, the low air density and the usual low air speeds of HAP make cooling by convection ineffective.
The climb and decent to around 20 km require a flight through the jet stream between 8 km up to 12 km. An ultra-lightweight structure easy struggles with the turbulences expected in the jet stream as the losses of the Helios [2] and Zephyr [8] showed in the past.
Lastly, long endurance flights and flights above the civil airspace in general will require a certain amount of reliability. However, this necessary reliability is difficult to achieve while aiming at wing loadings of less than 6 kg. In most cases reliability comes from robust design against wear or from redundant designs. Both solutions usually come with weight penalties due to additional or more robust components.

This is where research institutions such as the German Aerospace Centre come into play to find new ways to loosen up the contradiction of ultra-lightweight, yet robust and reliable designs.

3. The DLR Project HAP-alpha

In 2018, the German Aerospace Center (DLR) started its high altitude platform project with a budget of around 30 M€ and a run time of 5 years. At that time, it was the first big project centered around the build of a HAP of any research institution in Europe. The DLR gathered 18 institutes and facilities of the domains aeronautics and space to follow four main research goals in the area of high altitude platforms:

- Development of novel system concepts and technologies for the realization of robust and cost-efficient high altitude solar platforms
- Development and testing of innovative sensor systems for earth observation. In particular high performance is combined with highly sophisticated lightweight construction
- Development of operational strategies and mission scenarios to demonstrate the performance of high altitude solar platforms
- Demonstration and flight testing of novel technologies, processes and sensor systems

To reach these goals, the main focus of the project is the design and build of a full-scale high altitude platform including a ground station and two sensor systems as payloads.

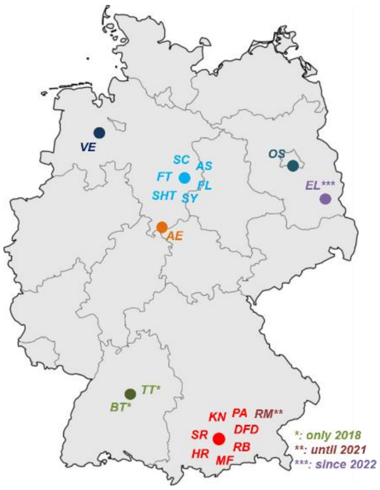

Figure 2: Participating institutes of the DLR scattered all over Germany

In 2022, the project runtime was extended by two years. The main goal of the runtime extension is the integration of the HAP-alpha to a fully functional aircraft 2024 and its maiden flight afterwards.
The design and build of an unmanned high altitude platform, such aircrafts usually have a wing span of around 25 m up to 35 m and more, including a ground segment as well as two light-weight high-performance sensor systems is a challenging task. This counts for the technological aspect as well as the administrative aspect bringing this number of institutes and a team of more than 80 people distributed over Germany close together. Project management within the DLR is usually done in a weak matrix organization. The weak matrix is characterized by the lack of authority over the team members and limited control over the project budget. To face these challenges and, in some point, to meet the concerns of having a weak matrix project organization within DLR, a strict Systems Engineering (SE) approach was chosen and is followed within the project.

4. Systems Engineering approach

The Systems Engineering approach followed within the HAP-alpha project combines well established traditional methods with modern Model Based Systems Engineering approaches.
The basic underlying SE process follows a variant of the V-Model and is shown in Figure 3. On the left side of the V is the overall design process depicted. The design process is a top down approach using multiple levels of detail to describe the overall system of interest down to the individual item. The number of detail levels depends on the system, but we have found that 3 to 5 detail levels are sufficient in most cases. The top level, L0 in our case, describes the overall system consisting of the platform itself and the ground segment. The bottom level of L3 or L4 describes devices such as a single actuator of the flight control system.

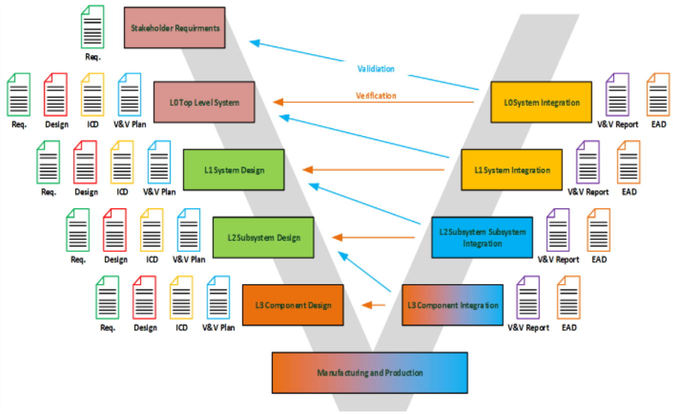

Figure 3: V-Model as used in the HAP-alpha project

Shown left of the design process is the documentation assigned to each level of detail that is written for each system element. In every level and for each assigned system element there are requirements, a design documentation of the final system element, interface control documents where electrical and data interfaces are described as well as verification and validation plans for all of the requirements.
Shown right on the V-Model branch is the integration process, heading bottom up, from the final single devices to the full system including a link to the design branch for verification and validation. Extended is the right branch by the documentation files provided at each of the stages. For each component and system there is a validation and verification report, gathering the outcome of all of the different validation and verification actions. In addition, there is accompanying documentation for each component, that contains a usage history of the component.
Coupled to the V-Model is a general development cycle that divides the development of the HAP-alpha in different phases. In contrast to the shown level hierarchy, the phases have a timely character and correspond to the project timeline. The number of phases used can vary from project to project. However, for engineering projects, such as HAP-alpha we found a cycle of 4 phases appropriate:

- Early Design – Stakeholder requirements are collected and transformed into high level system requirements. In the solution domain the top-level system is designed according to the requirements. This corresponds to the L0 level in the V-Model.
- Preliminary Design – In the problem domain the top-level requirements and the top-level system design are translated into high-level requirements for platform, ground segment and payload and later for their major sub-systems. In the solution domain the afore mentioned high-level systems are designed and later on, the major sub-systems accordingly. This represents L1 and L2 levels in the V-Model.
- Detailed Design – Each major sub-system is broken down in smaller systems down to single components with the same work flow as before; Requirements are derived from upper level and a design is developed to meet these requirements. Also, part of this phase is the extensive testing of prototype hard- and software. This conforms to L3+ level in the V-Model.
- Integration and testing – After the detailed design is settled and the bottom-level components are

built, they are qualified with the verification and validation process and stepwise integrated into larger systems according to the established level hierarchies. It must be noted, that in this phase the final hard- and software for flight operation is qualified and integrated. This phase is further subdivided into integration phases according to the level hierarchy.

In the HAP-alpha project, each design and integration phase closes with a final gate review.
These reviews are:

- System Requirements Review (SRR) after the early design phase
- Preliminary Design Review (PDR) after the major sub-systems are developed (L2)
- Critical Design Review (CDR) after final detailed design (L3+) is settled and prototype hard- and software close to the final flight hard- and software is extensively tested
- Test Readiness Review (TRR) after the components and major sub-systems are integrated to the high-level systems platform and ground segment. In this review it is determined, if the top-level system is ready for ground tests
- Flight Readiness Review (FRR) to determine if the top-level system is ready for its first flight and further flight testing

The SRR, PDR and CDR are conducted with DLR-external reviewers from industry and science community, who are experts in their domain.

In addition to the more traditional V-Model approach, the project also relays on modern model-based system engineering (MBSE) technics. For the development of HAP-alpha, we use a data model as single source of truth and the OMG Systems Modeling Language (OMG SysML) [11] as modeling language. Most of the content, such as requirements, interface descriptions and verification and validation plans is modeled using SysML and corresponding documentation is auto-generated from the data model. Regarding the system design, the system architecture (Figure 4) and interfaces between and within system elements are modeled.

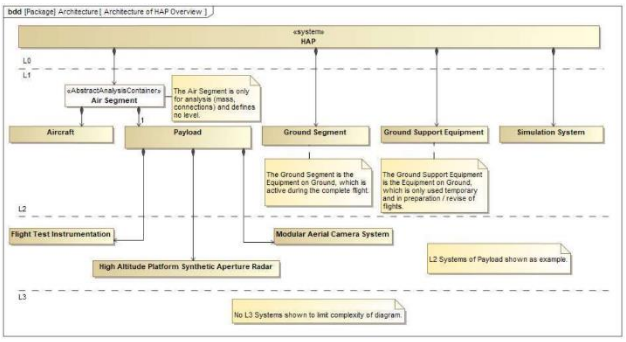

Figure 4: Example of the HAP System Breakdown, from level L0 down to L2

However, it turned out necessary to have the system design descriptions written in natural language extended by the use of diagrams and pictures generated from the model. Applying MBSE technics and modeling with SysML requires a decent amount of knowledge and skill in this area, which only a few team members have. Although even the system design descriptions could be made within the data model, we felt it was a reasonable compromise to accept possible inconsistencies in favor of better sharing within the team and with the reviewer. For future projects of similar scale, it is important that as many team members as possible, if not all, should have basic knowledge in MBSE technics and the modeling language used to be able to use them to their full potential.

In summer 2023, the HAP project is at the end of the detailed design phase and the team will have performed their critical design review when the paper is published. The methods and techniques chosen, while appearing to be quite simple, were wisely chosen as easy to understand yet proven approaches to fully focus on the challenging design and construction of a new solar powered HAP. Up to this point, the strict Systems Engineering approach seemed the right choice to make this ambitioned cutting-edge engineering project work. To some extent, the presented approach also compensates some issues inducted by the weak project organization common in DLR.

5. A platform for scientific experiments in the lower stratosphere

The unmanned technology demonstrator HAP-alpha is a full scale, solar powered high altitude platform. It has a wing span of 27 m and is designed for a cruise altitude between 18 and 20 km. With a target weight of 134 kg including a payload capacity of 5 kg and a wing area of around 36 m², it reaches a wing loading of 3.5 kg/m². As stated in chapter two, it is crucial for solar powered high altitude platforms to reach a wing loading below 6 kg/m².
In cruise phase, the HAP-alpha reaches an equivalent air speed of 9.0 up to 11.0 m/s. Its target weight is comprised of the following main components:

- Carbon fiber reinforced polymer (CFRP) structure with around 55 kg
- Drive train 59 kg of which 40 kg are the batteries only and 8 kg are the solar generator if fully equipped
- Avionics 14 kg of which are around 8.5 kg for wiring and interconnection
- Payload of 5 kg

Although HAP-alpha is designed as a solar platform for stratospheric use, the platforms' first iterations are reduced in capability for two major aspects. First, with the DLRs first attempt of a high altitude platform, long endurance flight testing is out of scope and a topic for follow-up projects. Thus, chosen battery technology as well as the amount of batteries in relation to the rest of the platform mass is not optimized for overnight flights.
Second, as a means of risk reduction in first low altitude flight testing, HAP-alpha is only equipped with a minimal solar generator. Regarding flight tests, we follow a three-stage approach, see figure 5. For first flight tests in low altitudes, HAP-alpha will be equipped with 1.5 m² of solar generator. In stage 1, HAP-alpha will be able to ascent up to 5 km and stay several hours in air. For mid to high altitude testing a second stage of the HAP-alpha with enlarged solar generator up to 12 m² is planned. A third stage with around 22 m² solar generator can be built once flight testing of stage one and two have been successful.
The stages one and two of HAP-alpha will use state-of-the-

art technology and commercial-of-the-shelf parts wherever possible. Thus, the drive train uses two modified commercial-of-the-shelf electric motors with 2.1 kw continuous power, standard Lithium-Ion batteries with a energy density of 240 Wh/kg and triple junction Gallium-Arsenide solar cells with a efficiency of 30% and a weight of 320 g/m².

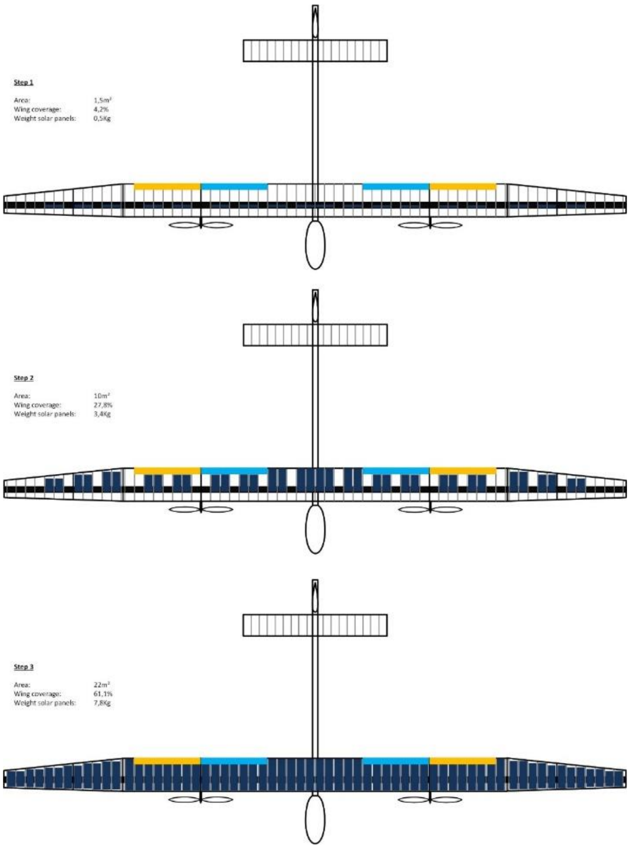

Figure 5: HAP-alpha design stages, solar generator coverage shown in dark blue; Stage 1 top, Stage 3 bottom

In addition to the platform itself, a fully functional mobile ground segment to operate the HAP-alpha is also part of the project. The ground segment consists of two major systems. The trailer-based communications station including antenna and the container-based operator station. Command and control are realized via bi-directional S-band link with up to 1 Mbps and around 250 km range. As standardized communication protocol we use the STANAG 4586 [12]. For sensor data such as data gathered from payload sensor systems a X-band downlink with up to 100 Mbps is used. Flight guidance is done with a version of the DLR U-Fly software, adapted for the use and needs for high altitude platforms.

A third part of the HAP-alpha project is the development of two ultra-light and powerful payloads for Earth observation, which will later be carried and demonstrated by the platform. The first payload to be carried will be a high-resolution camera system, the MACS-HAP (Modular Aerial Camera System) [13]. The MACS-HAP is an optical camera system with a high precision pan-tilt device. In 20 km altitude it offers a ground resolution of 15 cm and can be used for pointing and mosaicking. Thus, the MACS-HAP offers a persistent monitoring of an area or a single target.
The second payload to be carried is a radar with synthetic aperture, the HAPSAR. The highly integrated radar electronics enable for a ground resolution of up to 60 cm in 20 km altitude. Unlike the high-resolution camera system, which needs a clear field of view to its target and daylight, the HAPSAR [14] is fully operational under any weather conditions and at any time of the day.

While waiving the overnight flight capability for the HAP-alpha seems disappointing at first glance, the technology demonstrator in its second stage is still capable and ready to conduct scientific experiments in the lower stratosphere. It is able to climb up to 20 km altitude and stay there for around two hours before it has to start the descent. On the one hand, the experimental time in lower stratosphere seems sufficient for the HAP-alpha core ability; demonstration and test of sensor systems and new HAP technologies under real operational conditions. On the other hand, the relatively slow climb and descent rates of about 1.5 m/s result in long operating times of nearly 24 hours, which presents its own challenges for crew and operating procedures.

Once the stage two of HAP-alpha is reached and the crew has built confidence with flight operations to the lower stratosphere, the aircraft is ready to carry lightweight sensor systems as payload and to demonstrate their use.
In order to be able to carry both payloads and other loads with minimal integration effort, the payload bay or nose or head of the aircraft is designed to be as modular as possible. The payload bay's structure is designed to the payloads' specific requirements and is attached to a standardized mechanical and electrical interface, allowing an easy and relatively fast payload exchange.
Thus, the HAP-alpha is ready to operate any sensor system that meets the interface requirements as well as the weight and power limitations.

Besides the demonstration of sensor systems for earth observation, the second stage of HAP-alpha is also able to perform flight tests with new and promising platform technologies. One example for such technologies is the solar generator. The most widely used technology is a gallium arsenide-based cell in a triple-junction configuration. This cell type offers currently the best compromise of weight and efficiency. However, it is by a far the most expensive part of any solar powered platform with roughly 100.000 dollar per square meter. New and less expensive solar cell technologies that could reduce the cost of a high altitude platform need to be tested under real environmental conditions. As a flying testbed, HAP-alpha could be partly or fully equipped with such a new cell technology.
Other technologies, worth experimenting with, are batteries with high energy density and cold temperature resistance.

To foster civil aviation certification for high altitude platforms, new as well as safer but light-weight system designs for avionic components such as flight control computers or electromechanic actuators could also be integrated and tested on the HAP-alpha. As we stated in [15], the air space integration in civil air traffic is quite a challenging task, that makes new approaches such as the idea of a "higher air space" necessary. While a safe design is only one half of the solution, operational procedures and strategies for every flight phase are another. The second stage of HAP-alpha and further evolutions are suited to test, refine and train these.

6. Conclusions and future work

Throughout the paper we gave a brief summary of the history of solar powered high altitude platforms from the late seventies up to today. We showed that high altitude platforms have to face a quite challenging environment and must be carefully designed. Only few of the competing companies are still successful but not yet operable. There is still room for research institutions such as the German Aerospace Center (DLR) to find new and promising solutions for the contradiction of ultra-lightweight, yet robust and reliable designs. The DLR is gathering knowledge in the field of solar powered HAP using a holistic approach by designing, building, testing and operating the HAP-alpha, including a mobile ground station as well as two sensor payloads. We showed that we tackle the challenging engineering project with its large, distributed team and a weak matrix project organisation by using a strict Systems Engineering approach. Our approach is a combination of the well established and easy to understand V-Model and rather new MBSE methods such as a data model as single source of truth. In addition, we conduct reviews together with external experts from industry and science after each major design phase. Until now, half way through the project cycle, our approach turned out quite successful. We plan on sharing our findings using this approach in more detail in the future. After laying these fundaments, we gave a high level overview of our HAP-alpha and the two sensor payloads developed and built alongside. As last aspect of this paper, we shortly dived into the possibilities the HAP-alpha offers for future research, especially in stage two, where stratospheric flight testing of new technologies and sensor systems is possible.

In summer 2023, the HAP-alpha project completed the critical design review which was the latest important milestone. After successful manufacturing of the flight structure as well as all necessary flight hardware, all will be integrated to a complete high altitude platform in the next couple of months. Regarding first flight tests, such lightweight structures are very sensible towards wind and rain. Knowing that, only the summer months offer sufficient weather conditions for HAP flights in the northern hemisphere. Therefore, the first maiden flight opportunity is expected for summer 2025. Until then a huge amount of integration works and testing awaits the team. In between, a test readiness review will be done to show that the platform and the ground segment are ready for ground testing. All the integration efforts close with a flight readiness review to show HAP-alpha is ready for its maiden flight and further flight tests.
With its maiden flight, the flight test phase of the HAP-alpha in stage one starts. The crew needs to build confidence in operation as well as in the platform. Furthermore, the platform design developed over the last years needs to be proven. Especially in the fields of aeroelastic and control as well as structural design, flight test results are eagerly expected.
While the broad scientific use for HAP-alpha described in chapter 5 aims for stage two and beyond, the first flight test campaigns deepen the design knowledge and thus, already contribute to one of the DLRs main research goals:
Development of novel system concepts and technologies for the realization of robust and cost-efficient high altitude solar platforms.

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