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Lessons learned and the recent achievements of a three-stage suborbital rocket production

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Abstract

The project presented in this article, which consists in designing and launching a three-stage suborbital rocket with a 40 kg payload covers the subjects of the rapid development of a multi-stage proof-of-concept vehicle with a limited time to deploy. These finite resources and a negligible percentage of the technology available tested in-house in advance led to the implementation of chosen, well-known industrial solutions into the concept for a winning strategy. This paper presents the recent achievements and lessons learned from the production phase of the components, namely: the rocket motor, control section compartment, guidance and navigation bay, together with recent achievements and future challenges. This set of components, derived from the project, will fill the gap in the technological chain for future Polish launchers and munition. The three-stage suborbital rocket development project is divided into three phases, which will last a total of three years. The first phase is the conceptual design stage, along with laboratory tests of solutions and subsystems used in the rocket. The second phase consists in flight tests for individual stages, together with the decisive flight of a three-stage rocket made to reach the Kármán line. The final stage involves the commercialization of the developed technology and the creation of a service for carrying research loads of up to 40 kg. The project is valued at approximately USD 5 million. The project is co-financed by the National Centre for Research and Development (NCRD) as part of dedicated support for the Polish space industry.

Keywords: production of rockets, three-stage rocket, suborbital stage, missile defense, aircraft defense

1. Introduction

The history of sounding rockets launched from Europe is rich and trailblazing and has been well summarized by Seibert (2006). America's heritage is just as impressive, with a long-lasting, consequent rocketry program execution (Corliss, 1971; Wells et al., 1976) with hundreds of Black Brants and other rockets launched. The Scout Launch Vehicle Program (Foster & Urash, 1981) utilized a selection of motors produced for the U.S. Department of Defense to set up a four-stage vehicle that would be low-cost and reliable. Over the years, that enabled assessing Scout orbital capabilities and reentry missions. The single-stage sounding rocket concept is now trending to replace old designs using surplus military rocket motor setups (Okninski, 2017), which is connected with the extensive development of hybrid engines (Faenza et al., 2017). Ramjet-based "aerospaceplanes" are being introduced (Russo & Voto, 2023) and the use of near space for the development of science through low-cost and adjustable suborbital flights is currently at its best (Fitzpatrick, 2020; Rasanova, 2022). Suborbital missions are constantly pushing the frontier of science with

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courageous and agile experiments on electromagnetics, telecommunications, remote sensing, education, entertainment and better connected with all of the potential exploration areas – earth, air, orbit and deep space. This yields the need to constantly develop and improve existing designs, and exchange and maintain competencies on the local market to be independent and have optimal solutions.

Polish works of the Institute of Aviation have been focused on developing a new green propellant, single-stage vehicle with the aid of a solid-propellant booster vehicle (Marciniak et al., 2017). This vehicle is meant to be stabilized aerodynamically in flight. It is being prepared to lift a 10 kg payload above the 100 km Kármán line. A private Polish company, SpaceForest, is intensively working on their PERUN vehicle (SpaceForest Ltd., 2023). Their work concentrates on developing a single-stage hybrid rocket motor with a total impulse of over 1.2 MNs. They have developed their own thrust vector and reaction control systems for stabilization.

The project presented in this paper involves the design, prototyping and demonstration flights of a three-stage recoverable rocket and, as a result, the implementation of a range of technologies and products for space applications to be performed more cost efficiently, safer and ever further rocket flights in Poland, launched from Polish testing centers. This cooperation was initiated by Military Aviation Works No. 1 (leader) and is supported by The Special Production Plant *GAMRAT* and the Military Institute of Armament Technology. Consequently, the result of the project is the first suborbital flight in Poland based on a multi-stage rocket with solid-propellant motors. The research and development work undertaken will result in the development of a carrier system competitive on the European market, capable of reaching the space barrier – the 100 km apogee – and lifting payloads of up to 40 kg.

Work presented in this paper provides the insights of the design of verified designs of the three-stage rocket system; where, a series of technologies developed in the design process can be drawn from it and applied for further use separately. From the safety and defense requirements point of view, there are rocket subsystem prototypes produced which can be named *dual-use*. Among all of the components there are few meant: the solid rocket motor with a composite case, characterized by a 200 mm diameter, 300 mm diameter and 600 mm diameter with custom igniters, the safe and arm system and the casting line for a composite propellant for these volumes; the flight termination system; composite body structure, pyrotechnical stage separation mechanism and the aerodynamic control system with an autopilot and inertial navigation system, tuned for suborbital path correction. Since the process has been established, it can be refined to match this demand. Historically, surplus military technologies have been employed in suborbital projects; however, in this project, it was found suitable to turn this trend around.

It is important to recognize how localized dual-use suborbital design can be beneficial for the armed forces, which is the thesis of this paper, and what decision process was involved in the choice of the solutions. Quality products with modern technologies applied can be delivered with an affordable budget, which is presented. This improves the safety of munition supplies and guarantees independence from suppliers. It is crucial for an effective deterrence strategy. The system is optimized, and improvement can be applied under local governance with no export control. The steps taken to achieve these state-of-the-art results in no time are discussed in the following sections.

2. Subscale rocket

The subscale rocket with a diameter of 105 mm was developed to enable access to flight testing prior to suborbital-type test bed production. The main properties are listed in Table 1. The rocket's overall view is presented in Figure 1. It is common practice to use downsizing to prove the design prior to achieving the full-scale (Yonemoto et al., 2018). It has enabled the possibility to verify all the assumptions on the go and led to outperforming design requirements. A number of test flights saved the project from wasting valuable resources and electronics in premature failures on a full scale rocket. Easier handling and storage led to faster preparation time of a vehicle. Up to the first quarter of 2023, a number of seven flights with full avionics integrated were possible. Each flight enhanced control algorithms and issues detected on anterior one. Proper tuning of amplification was the main goal of all the experiments. With limited time, some of the testing were skipped, and the technologies were chosen arbitrally, with regard to available technologies and the components market. The aim was to determine, while going with the flow of the schedule, whether there was a need to enhance the properties of certain systems, or whether the requirements were fully satisfied.

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Table 1. The main parameters of the subscale rocket

Constant	Value	Unit
Diameter	105	mm
Booster diameter	200	mm
Length without booster	2 315	mm
Length with booster	3 311	mm
Mass without booster	15.6	kg
Mass with booster	46	kg
Mean base motor thrust at sea level @ 23°C (measured)	8 200	N
Mean booster thrust at sea level @ 23°C (designed)	12 000	N
Maximum chamber pressure @ 23°C (measured)	11.7	MPa
Maximum chamber pressure @ 23°C (designed)	7.9	MPa
Maximum flight speed without booster (measured)	1.88	Mach
Maximum flight speed with booster (designed)	3.5	Mach

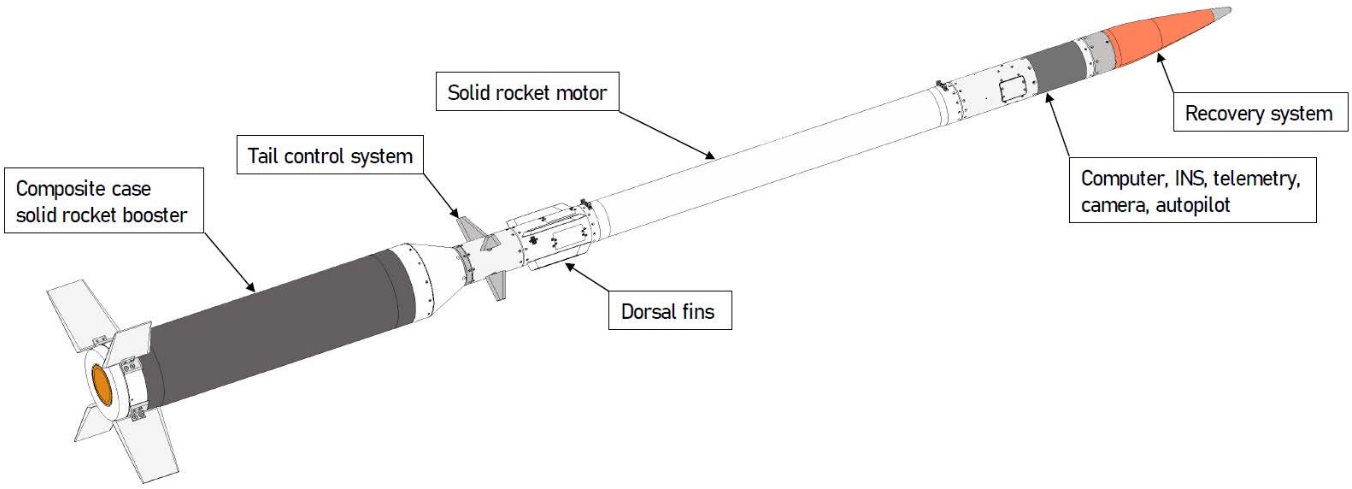

Figure 1. Subscale rocket with booster overview

The aerodynamics and tail-control section with stabilizers was developed using semi-empirical methods supported by CFD data. This led to a highly maneuverable structure. Power electronics with electric, brushless motors were integrated in a backlash-free drive section to match the surfaces' aerodynamical properties. The control section provides up to ± 30° angle of motion on each fin with a speed of up to 500 °/s. These values are proper for highly maneuverable rockets (Javier, 2016). A solid rocket motor with an aluminum case and a blast tube was manufactured using machining. Extruded double-base propellant grain was used to accelerate the rocket. Dimensions (diameter and length) dictated the use of a star shape in the grain, which produced over 60 *g* of overload at the start. The team willing to use a high-end inertial measurement unit with negligible drift over this short flight for sensing, was limited with 16 *g* value cap of acceleration in the main axis of the body. To solve this problem, a number of rocket motor tests were conducted under different environmental conditions to determine the exact performance of the motor and to substitute the data from the start in the control unit. Further flight performance is dictated by the quality of work of a GPS unit, which provides updates to the rocket position.

The body frame of the subscale rocket was made using machining. All of the mechanical components were manufactured by the project consortium. At the preliminary stage, for this diameter of rocket, it was the proper technique in order to produce a few experimental sections. Handling and storage with this size of a rocket was not an issue. All the tooling needed for testing and manufacturing was available on the go. While preparing for a full-scale test bed handling, a series of considerations were to be taken to enable the project to go.

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The booster of a subscale rocket consists of a filament-wound cylindrical case, an extruded propellant grain with a cylindrical port burning from all the open surfaces, and a nozzle. The igniter is common with the base rocket motor of the subscale rocket. The process of booster case preparation is a common part of manufacturing the motor case for the suborbital rocket. It is equipped with stabilizing fins and detaches mechanically when the deceleration hits its body. It also demonstrates the technology used to develop the three-stage rocket standard motor. The manufacturing method was not the only one proposed, but filament winding offered a much more lightweight structure in this diameter with little additional tooling. This ended with the successful testing of the case with 18 *MPa* od hydrostatic pressure, which fulfills the factor of safety with a value of 1.5. It has not been flown yet.

To verify the performance of a subscale rocket, there is a downlink with 32 parameters sampled with a frequency of 100 Hz. In Figure 2, one can see the normalized notation of acceleration in three coordinate axes. Data were gathered from one of the test flights. At first glance, the area of sonic phenomena falling within 7.5 *s* on the *AccX* curve seems typical. In the authors' opinion, is the minimization of accelerations in the pitch and yaw channels after switching on the control systems is also of interest. Later in the flight, once 20 *s* have passed, the effect of the symmetricity imperfection of the mass distribution in the rocket and the occurrence of deviation moments can be seen, which translated into the occurrence of *AccY* and *AccZ* overloads with a rotating motion in the roll channel, which was inevitable at that moment. These results come from Sokolowski et al. (2023), but they have also been found worth mentioning by the authors of this material to give an overall view of the recent advancements of the project. This proves that research on aerodynamics, flight dynamics, evaluation of control section and simulation methods were valid, which is verified by the proper work of the autopilot controlling the supersonic vehicle. This process was developed with a multi-disciplinary team, which gathered the available materials, techniques and tools and critically integrated it into the working subsystems.

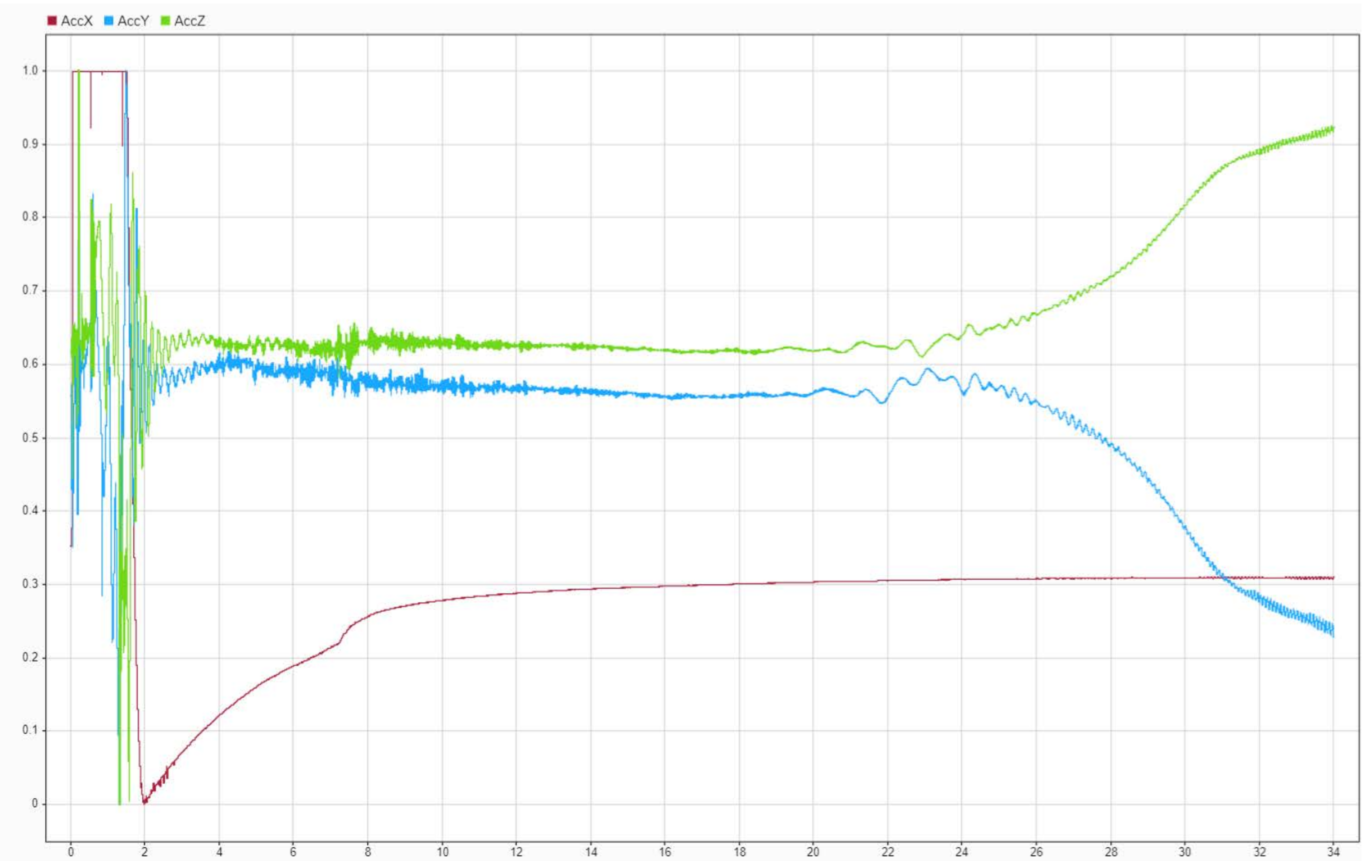

Figure 2. Normalized notation of acceleration. Adopted from the work of Sokolowski et al. (2023)

The flight of the rocket was recorded and tracked by cinetheodolites. The lift-off and separation of the recovery stage of a subscale rocket can be found in Figure 3. Using this tracking equipment provides a second layer of confirmation of the performance of a rocket. The Military Institute of Armament Technology is the only operator of such a system in Poland. Details of how this idea is implemented and used, and how the data from the recorded frames is processed can be found in the work of Kaniewski et al. (2019).

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The effects described here were achieved in a two-year period of time, utilizing no more than USD 500 000 (production of ten prototypes and tooling, purchase of navigation components, labor hours, etc.) and starting from just the overall concept. The design is easy to operate, includes lightweight materials (aluminum, carbon-epoxy composites) and can be further improved to realize more advanced missions for military purposes. To name a few – a very short-range anti-aircraft effect, short-range anti-effector, and a counter-uncrewed aerial vehicle, while using booster or boost-sustain-boost motor configuration. Rapid prototyping and multiple testing scenarios used have drawn a fast learning path. The presented parameters are adequate and can be further adjusted, as the whole design is localized and can be freely modified by the project team members under the supervision of the Polish Ministry of Defense, in opposition to integrated solutions from multiple abroad contractors. Such an agile rocket was an outcome of the test bed prototype, which was found to meet various mission scenario requirements.

Figure 3. Cinetheodolite frames from the recording of the flight. On the left: lift-off event; on the right: separation of the recovery system

The main gaps filled in the current market state, which are being sustained by a sub-scale rocket design, include:

- INS navigation and proportional control system
- All the testing and production is in three companies, which are regulated by the local government
- Rocket motor design ready to match the requested scenario
- Full control over a supply chain and design materials and a full flexibility to adjust those if needed

None of these progress can be sustained with imported, regulated and controlled missile technologies and equipment. Quantitively and qualitatively in time, spendings and number of missile effectors to be delivered this solution will overcome on the long run every solution imported from abroad. Additionally, the consortium is able to evaluate the design with proper techniques and equipment to produce the military-grade weapon, improve logistics and warranty, and prolong the life of rockets after the lifespan ends. Currently, the production of similar systems does not exist, and the need for sufficient deterrence is counted in thousands.

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3. Three-stage suborbital rocket

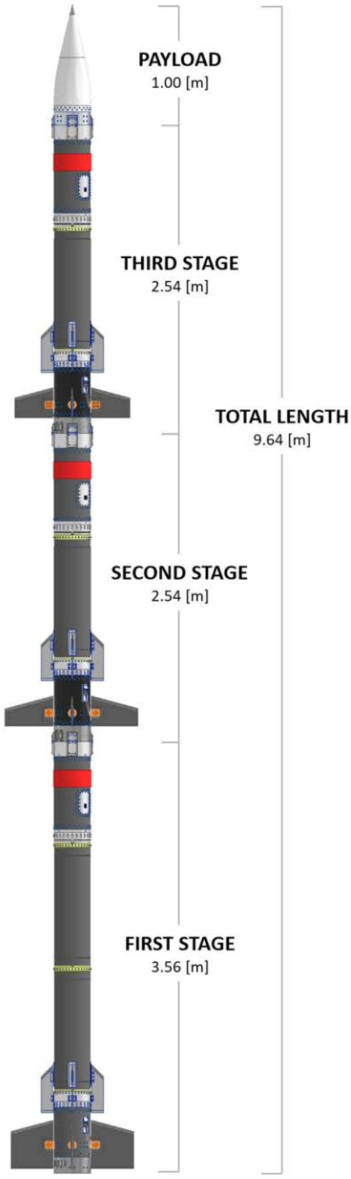

Figure 4. Three-stage rocket overview

There were numerous possibilities to design all the components of the three-stage suborbital rocket. Enhancements from the subscale rocket and storage and handling restrictions were introduced into the design of all components. The production of a few prototypes of each of the sections led to the accommodation of new technologies of production and administration of resources, which allowed the prototypes to fit into a tight schedule and financial plan, despite the COVID pandemic and the invasion in Ukraine, which changed the economic situation drastically. The final render of the rocket can be found in Figure 4.

Aerodynamics was altered for a three-stage version, which, with its high fineness, restricted the angle of attack on the first and second stages. Structure would not pass the high g maneuvers, when it is enlengthened so much. The previously presented pair of dorsal wings with tail fins was used for all of the stages. The area of the surfaces was chosen to provide a static stability margin of at least one diameter through the velocity range, which is valued at a maximum of Mach 5.6. Without enough tunnel testing and no infrastructure available to fit such a large model, assuming a smaller margin was impossible.

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When taking this velocity range into consideration, preparing an outer structure to be able to withstand aerodynamic heating was required. A series of tests of ablative materials were conducted. Thermal stresses were accounted for, and composite structures with aluminum stringers were developed for actuated fins. Stainless steel leading edges were introduced but separated with a carbon-phenolic sandwich from the rest of the structure. The outer structure is painted with low conductivity paint with ablative properties based on glass beads. After being charred in a hypersonic regime, the paint-produced gases will be blown away from the raw material, removing the excessive heat flux from the boundary layer. The nose has been constructed out of a glass-phenolic composite, which is also transparent to electromagnetic waves. This might be a feature for future developments of a radar-homing device if installed on the altered version of this vehicle.

A solid rocket motor with a diameter of 300 mm was developed with the lessons learned from producing a booster for the subscale rocket using filament winding. Machining such a big piece of metal had no business justification. Stir welding aluminum or laser welding steel rolled plates with machined flanges would introduce massive uncertainty into the performance of such a connection when tested on a few prototypes. If valid technology was required, the winder was introduced. Finite element calculations proved that the design of layup [55°/0°/90°]s can withstand given loads, but the geodesic representation of the winding path was not going to produce such a layup over the whole cylindrical surface and particularlly will not provide perfect representation over the aluminum flanges, which were introduced to allow for connecting multiple segments and easier stacking of segments with different propellant grains to match various mission profiles. Those flanges served as nearly perfect axial connection with the rest of the structure, which is crucial for overall assembly and quality of the geometric representation by the aerodynamic coefficients fed into the control algorithm. With proper tooling design, the problem of stacking up such a layup was later solved. The motor can withstand the pressure of at least 12 *MPa*, but the design and test pressure is 8.2 *MPa*. A typical pressure vs. time curve of a hydrostatic pressure test is shown in Figure 5.

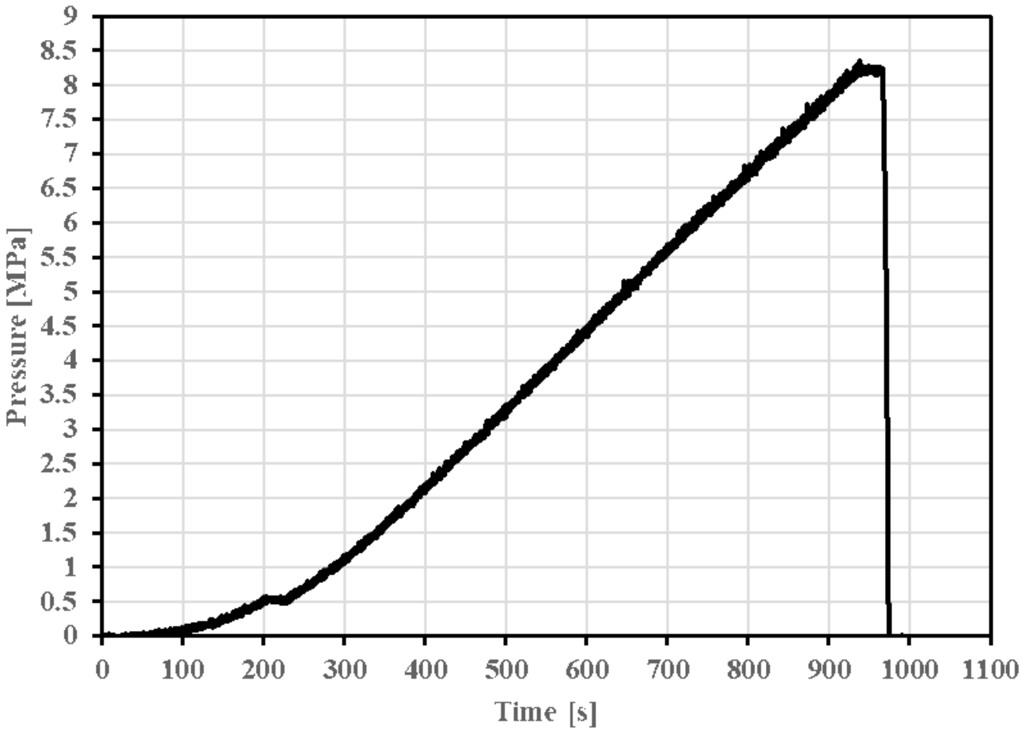

Figure 5. Pressure versus time curve of a hydrostatic test of 300 mm diameter rocket motor segment

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Figure 6. Three-stage rocket solid rocket motor with its blast tube type nozzle shown at MSPO 2022 event

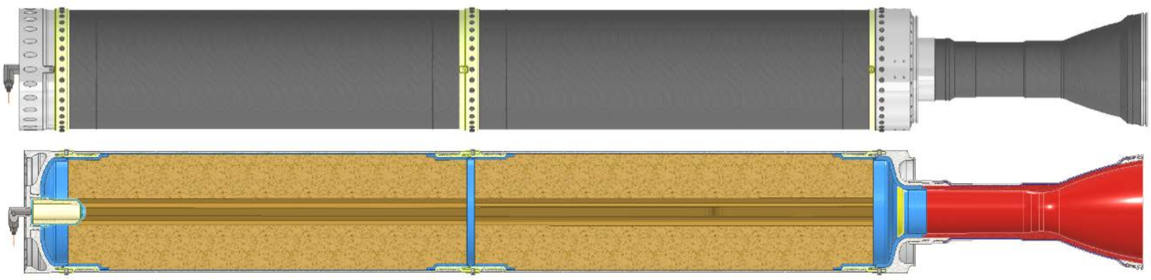

Figure 7. Three-stage rocket dual segment solid rocket motor model cross section with a blast tube

Figure 6 and Figure 7 show the rocket nozzle designed for a single segment of a 300 mm diameter rocket motor. It is made of carbon-epoxy with aluminum flanges and an internal carbon-epoxy 0° layup. The grain is star-shaped. Extensive propellant tests allowed for the design, which can employ erosive burning, thus increasing volumetric efficiency of the motor. Single stage weights after all these considerations, with proper seals, igniter, environmental plug and between section sealing roughly 140 *kg*, blows the flume with the mean force of 30 *kN* with a total impulse of 220 *kNs*. These numbers for dual-segment motors are respectively valued as: 230 *kg*, 75 *kN* and 450 *kNs*. Segments were introduced due to limitations in the size of casting line room. There is a project to make a monocoque, which could be used as a boost-sustain motor or even three-stage motor with boost, sustain and delayed terminal phase thrust profile. Development and testing of this crucial technology enables the path to suborbital flights; however, it can be tailored for other client needs. The reduced smoke propellant is being developed, and a smokeless alternative is being investigated for the refined rocket motor revision.

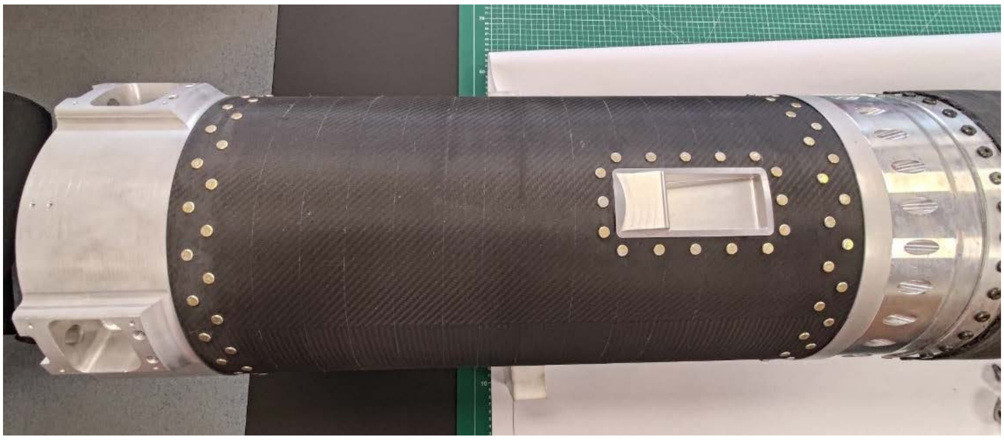

Figure 8. Computer and guidance section – prototype view with no coating

Figure 8 represents the current iteration of the raw composite section of the computer and guidance bay. The control electronics, INS, stage recovery, and flight termination system are stored there. There is a dual-link telemetry mounted on the board, whose ground station is shown in Figure 9. The section uses aluminum flanges connecting the part to the motor and the next stage – through pyrotechnical bolts. The carbon-epoxy prepreg overwrapped cylindrical part has protuberances for mounting umbilical connectors. All of the aluminum parts are connected with the composite through Hi-Lok fasteners. This state-of-the-art technology is mass efficient, freely adjustable and, thus, relatively cost-effective for advanced designs, suitable for a modern aerial vehicle.

Figure 9. Telemetry ground station used for three-stage suborbital rocket project. Image courtesy: SpaceForest Ltd

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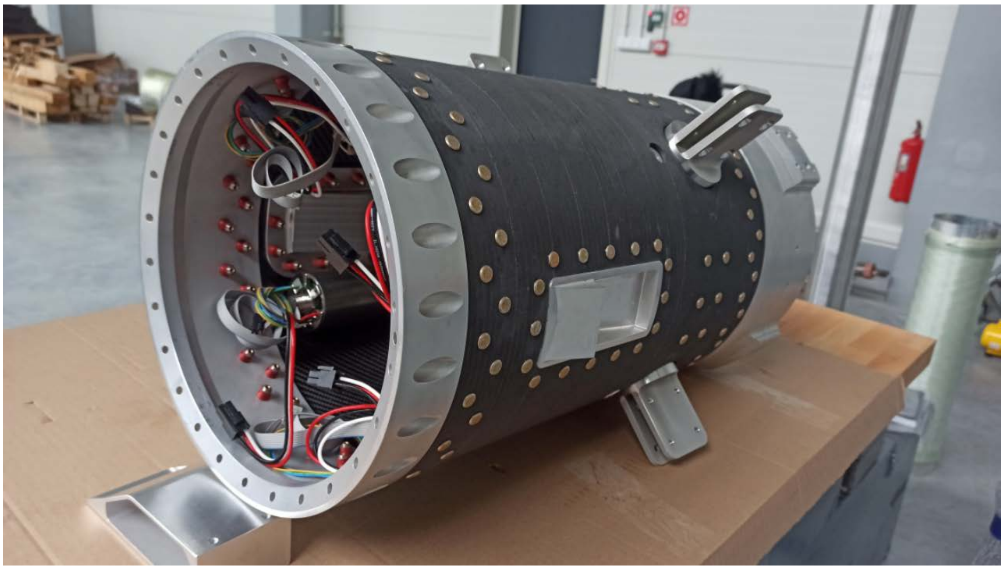

Figure 10. Control section bay – prototype view with no coating

An early version of the control section of a three-stage suborbital rocket is presented in Figure 10. One can see brushless motors installed with the hidden inside, but the flight-proven scheme of backlash-free drive tested on the subscale rocket. Massive grips for the aerodynamic surfaces were introduced to handle hinge moments rated for as much as 40 *Nm*. The electrical control system enabled the subsystem to have a mid-to-high natural frequency with adequate power electronics. For prototype purposes, all the power is stored in Li-Ion battery packs.

The concept was realized according to the plan, but the modern composite structure design solutions were to be implemented instead of the first metallic approach to produce cylindrical bodies for all subsystems. State-of-the-art connections were proposed, and their performance was tested and evaluated. The market analysis results in no proper machining techniques or contractors viable to deliver proper quality materials and manufacturing. This led to TRL 7 design, with TRL 9 solutions from subscale rocket, which will soon be proved during the suborbital flight from the Polish coast. The components were manufactured and integrated by the Military Institute of Armament Technology and Military Aviation Works No. 1 team members. and critical testing was performed by the Institute. This rocket can be used for military purposes as a ballistic target, medium-range anti-aircraft missile or artillery munition - technologies can also be used to design a rocket motor-booster gliding bomb, such as a GLSDB.

4. Summary

The project's introduction led to the development of crucial dual-use technologies for the Central-Eastern Europe suborbital market, and advancements were presented. The Military Institute of Armament Technology is known chiefly for testing military equipment. Company achievements and investments in R&D departments, connected with the production of components held by Military Aviation Works No. 1 and propellant production improvements from *GAMRAT* led to many successful flights, which resulted in data gathered pushing the project further. Successes and failures of the project in numerous rocket and missile, safety and defense, areas led to the development of multi-disciplinary know-how, which is invaluable. The aim of enabling the safe suborbital launches ended in a preparation of ready-to-use technologies based on modern subcomponents. All the design processes were acknowledged and documented for introduction into oncoming projects. The three-stage suborbital rocket's first flight is scheduled for November 2023. Three years of constant funding was enough to reach major milestones and gather the crucial crew-powered know-how and techniques, but there are years of improvements on the way. Such a base from a suborbital rocket can fill the market gaps for the military, which were exposed after years of no real conflict in Central Europe, where a lot of ageing post-Soviet equipment is being withdrawn. Local products are indeed fulfilling many of the gaps on the market. No export control over European designs is a critical advantage to enable users to put the proposed products into the ant-access area-denial systems.

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Declaration of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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