



Suborbital Rockets in Safety & Defense Applications

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Abstract

This paper presents benefits from using suborbital rockets in safety & defense applications. The paper describes suborbital rockets and their contribution to modern science, research and technology development. A historical view of suborbital rockets and their applications in safety & defense roles is discussed. Chosen research & development activities, military exercises and air defense systems' tests performed using suborbital rockets in various countries are listed and described based on a literature review of publicly available sources. The paper presents capabilities of Łukasiewicz Research Network – Institute of Aviation in the field of suborbital rockets. A development of ILR-33 AMBER 2K rocket reaching flight speeds over Mach 4 and optimized to reach 100 km altitude is described with comment regarding its applicability in safety & defense applications supported by flight simulations.

Keywords

rocket, safety & defense systems validation, sounding rocket, suborbital launch vehicles

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1. Introduction

The “suborbital launch vehicle” or “suborbital rocket” is defined by the Office of Commercial Space Transportation (part of the FAA – Federal Aviation Administration) as “a vehicle, rocket-propelled in whole or in part, intended for flight on a suborbital trajectory, and the thrust of which is greater than its lift for the majority of the rocket-powered portion of its ascent. The Suborbital trajectory is defined as the intentional flight path of a launch vehicle, reentry vehicle, or any portion thereof, whose vacuum instantaneous impact point does not leave the surface of the Earth” (Electronic Code of Federal Regulations, 2021). This definition clearly separates suborbital rockets from orbital launch vehicles which are often confused by non-specialists. While orbital launch vehicle provides with at least orbital speed and allows its payload to enter the orbit, suborbital rockets can only lift its payload to high altitudes - sometimes much higher than LEO orbits – but an orbit insertion is not possible. Such vehicles are often referred to as “sounding rockets”, however, in this paper the term “suborbital rocket” is used as a general nomenclature for such vehicles. Clearly, FAA definition as stated here with no context encompasses missiles, however, term suborbital rocket is used in a framework of rockets with no warheads and no direct combat roles.

An ability to fly above the Kármán line, achieved speeds, accelerations and other flight parameters make suborbital rockets useful for numerous applications in science, technology development and safety & defense. Civil applications of suborbital rockets were discussed by (Christie et al., 2016) with an emphasis on the activities in the United States. More general overview of suborbital rockets and their payloads was given by (Noga & Puri, 2020).

Civil applications of suborbital rockets are well described in the literature and in the public domain. On the contrary, safe & defense applications are often lacking technical description in sufficient level and were not described holistically. The goal of the paper was to attempt to close this gap and to preliminary verify a Polish potential contribute to safety & defense applications of suborbital rockets. The main research problems of the paper presented were ~~was~~ to:

- 1) Determine how suborbital rockets are used in safety & defense applications
- 2) Extract mission requirements and verify preliminary how Polish suborbital rocket with the highest Technology Readiness Level – ILR-33 AMBER 2K – can respond to these requirements.

The methodology to address research problems included a detailed literature review of civil and safety & defense applications of suborbital rockets. The review was limited to publicly available sources and included books, conference proceedings, scientific papers and press. Analysis of the data gathered in a literature review - especially use-cases – allowed to determine and to examine applications of suborbital rockets and corresponding mission requirements. Simulation data allowed to compare ILR-33 AMBER 2K mission parameters with derived requirements. In section 2 a construction of a typical rocket is detailed and typical applications in the civil sector are outlined. Section 3 presents numerous applications of suborbital rockets in safety & defense and – where applicable – briefly describes specific, historical missions. In section 4 technologies related to suborbital flights that are being developed in the Łukasiewicz Research Network – Institute of Aviation (Ł-IoA) are described with emphasis on ILR-33 AMBER 2K rocket. Paper’s findings are concluded and future work is proposed in section 5.

2. Suborbital launch vehicles – their construction and applications in civil sector

While most of the historical suborbital rockets utilized solid rocket motors such as military surplus motors (NASA, 2019), modern solutions often make use of liquid propellants as is the case for Nucleus (Faenza et al., 2019), MIURA-1 (Francisco et al., 2018), ILR-33 AMBER (Marciniak et al., 2018) and New Shepard (Blue Origin, 2019). The latter is an interesting example of a rocket with a demonstrated reusability and ability to land using its propulsion system – similarly as is done with Falcon 9 launch vehicles. Regardless of the propulsion systems onboard, such rockets usually have an experiment module where various types of experiments can be flown and a service module which includes avionics (flight computer, power system, communication system etc.). A parachute recovery module is often employed as well.

Rockets with high performance in terms of altitudes achieved and masses of payloads usually employ staging – in a manner similar to launch vehicles. An example of a rocket with exceptionally high performance is the Black Brant XII-A which utilizes 4 stages and can deliver over 90 kg of payload to an altitude of over 1600 km. The altitude of a suborbital rocket is driven by a total impulse of the propulsion system, its thrust curve (optimization of which is the objective of the famous Goddard Problem (Goddard, 1919)), a payload mass and an elevation angle. The latter is dependent on various factors, most notably wind conditions at launch. An example performance graph showing altitudes achieved when varying an elevation angle and a payload mass is shown on a Figure 1. It is worth noting that the impact range can be significant – even for a relatively small Improved Orion rocket the impact range can be over 100 kilometers. This drives requirements for thorough safety analysis including statistical computation of impact points and other methods (Wilde, 2018). Figure 2 presents an example trajectory and flight-events of a suborbital rocket. The rocket launches from a launch rail using its rocket propulsion system – cold launches are most often not implemented. Once one or more stages have finished thrusting the rocket decelerates and its altitude is increasing until the vertical component of the velocity is zero. When this happens, the rocket is starting to fall down. Some segments (especially rocket motor stages) separate during ascent, however, at times separation can occur during the descent. So-called flat spin phenomenon is utilized to reduce the speed of the rocket during the descent. A two-staged parachute is often employed to further slow-down parts of the rocket intended to be recovered. Recovered parts are most often the experiment and service module. New Shepard rocket demonstrated ability to recover the whole vehicle.

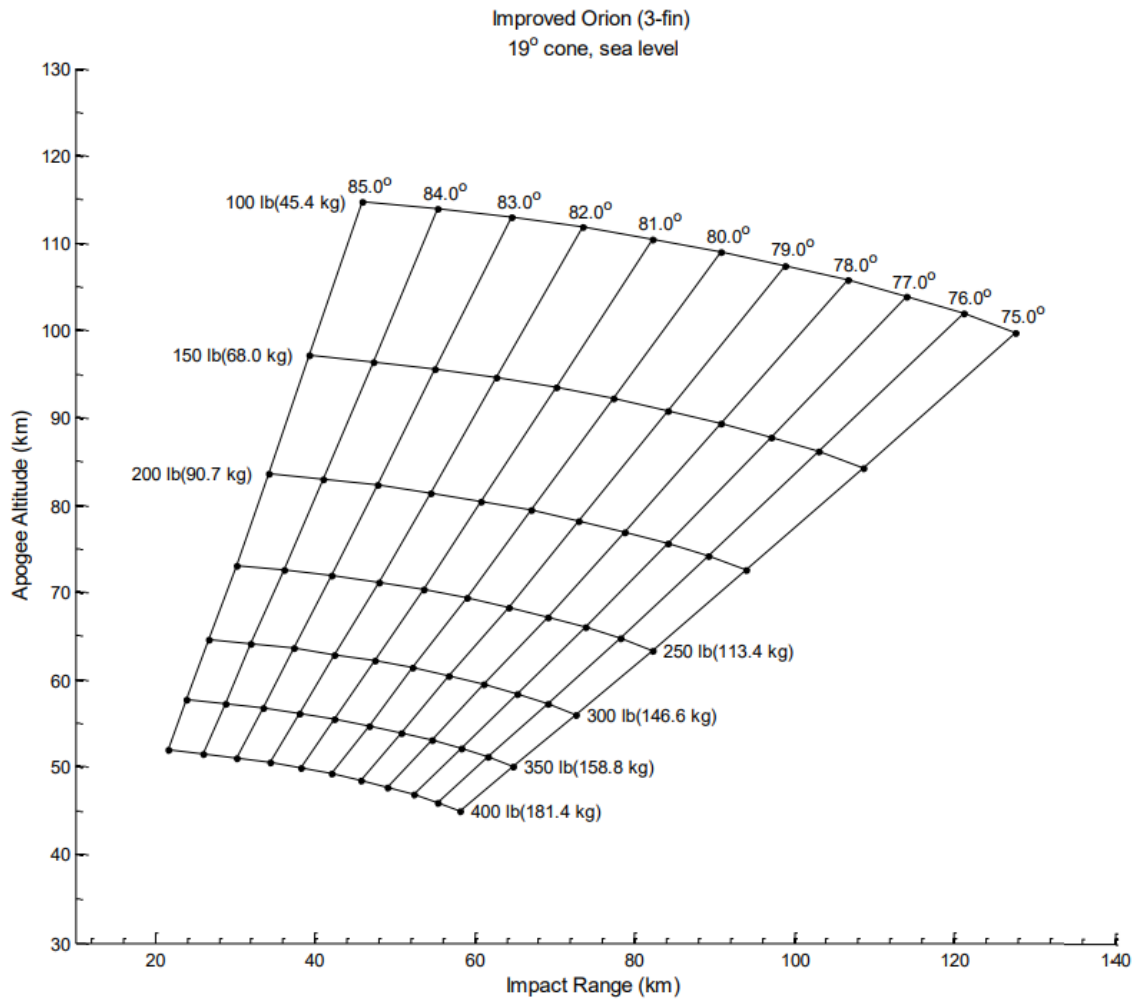


Figure 1. Performance Graph for Improved Orion . Adopted from: “NASA Sounding Rockets User Handbook” by NASA. Copyright 2015 by NASA.

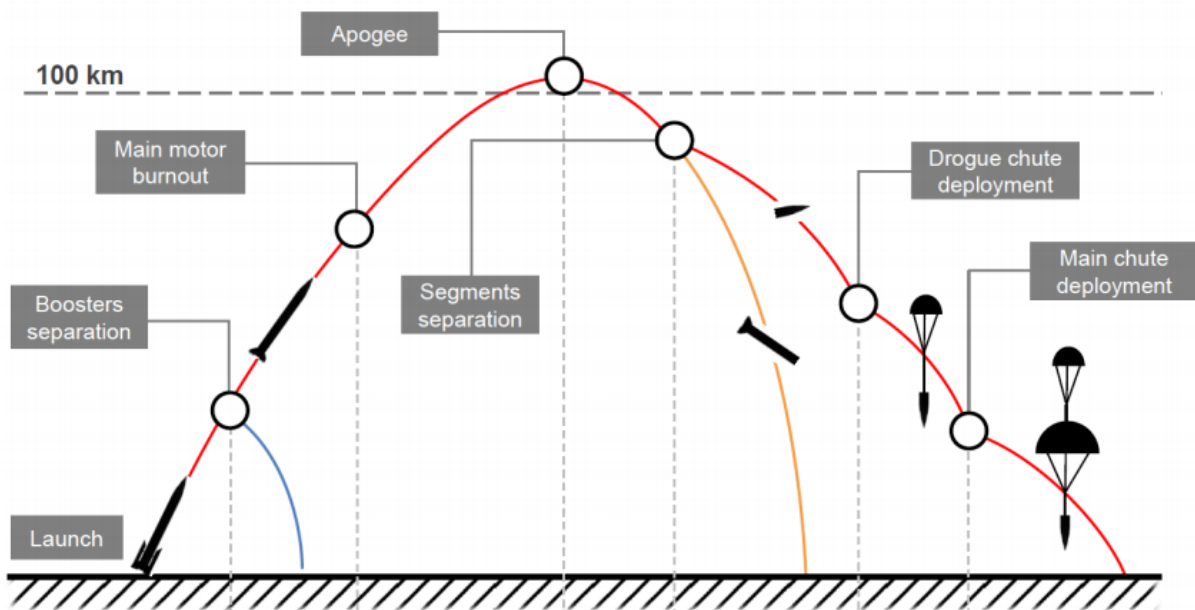


Figure 2. Trajectory of ILR-33 AMBER 2K rocket. Ł-IoA own work.

Suborbital rockets are usually launched from spaceports that include launch rails, integration halls, ground stations, mission control rooms, meteorological equipment, and more (Noga & Puri, 2020). Some entities demonstrated ability to launch the rocket with a mobile ground infrastructure – example being Ł-IoA launching AMBER rocket from military test grounds in Poland.

Suborbital rockets have seen service as early as in 1946 when a captured German V2 rocket was launched from the White Sands facility (Demets, 2011) to perform research on effect of brief space travel (an apogee of 187 km was achieved) on a fungus. Research was continued with more complex species and new research fields were studied. Biology and astrobiology is an important topic of suborbital research to date. Atmosphere sounding has started in 1947 and to this day it provides data regarding structure and processes of the Earth's atmosphere (Noga & Puri, 2020). Suborbital rockets are the only vehicles that can gather the in-situ atmosphere data in a feasible manner at ranges from approximately 40 kilometers (upper limit of stratospheric balloons) to 200 kilometers (lower limit of satellites). This type of suborbital research was especially popular in 1950's and 1960's (Seibert, 2006).

Another type of a suborbital research is a microgravity research. Microgravity conditions are experienced inside the suborbital rocket for some part of a flight ranging from 2 minutes for small rockets to even 15 minutes for larger vehicles. Suborbital rockets provide microgravity conditions of much better quality than aircraft and for higher durations than drop towers and aircraft. While a spacecraft can offer microgravity of comparable or higher quality and for much longer duration, suborbital rockets offer lower experiment price, faster turn-around and ability to recover the payload which is a driver for many types of missions (Noga and Puri, 2020). For instance, microgravity onboard suborbital rockets is used to precisely measure thermophysical properties of liquid metals (Egry, 2009) or to study response of living organisms to a gravity stimuli (Demets, 2011).

Suborbital rockets are platforms that can enable astronomical observations above the Earth's atmosphere. Observations above the atmosphere are vital as certain wavelengths of EM spectrum cannot go through it and any light reaching the observer on the ground is obscured. Astronomical observations from suborbital rockets are especially popular in the United States, and such observations allow to use cutting-edge observation technology which is not possible in case of spacecraft due to their cost and long mission preparation phase. At times, new detectors are flight tested onboard suborbital rockets before being used on spacecraft (NASA, 2019).

Astronomy is not the only field in which technology development can benefit from an environment onboard suborbital rockets. Such environment can be used to increase *Technology Readiness Level*, most notable in a space sector. Examples include tests of flight environment monitors, surveillance broadcasting, navigation sensors, avionics and other technologies dedicated for rocket vehicles – orbital and other. Entry, descent and landing technologies (i.e. for Martian Earth Return Capsule) were tested using suborbital rockets as well. In China, a number of commercial cubesats were launched onboard a suborbital rocket as part of test campaign. Space technologies related to liquid management in microgravity are another notable example (Noga & Puri, 2020).

It is also worth noting that suborbital rockets proved to be optimal platforms for education purposes. Educational programs in USA enable students from all levels of education to fly experiments of their designs onboard suborbital rockets.

An emerging type of suborbital flights is related to a space tourism. Suborbital flights can offer experiencing microgravity and being present above the edge of space for several minutes for a fraction of cost of an orbital flight. At the moment of writing such capability was demonstrated by Blue Origin and Virgin Galactic companies (Masanuga & Mendez, 2021).

3. Suborbital launch vehicles applications in safety & defense

As in case of purely civil applications of suborbital rockets, safety & defense applications take advantage of environment provided by such rockets. Review of publicly available information regarding safety & defense applications of suborbital rockets allowed to summarize them into following categories for the purposes of this paper:

1) Missile attack simulation

Suborbital rockets are in many ways similar to missiles – a classic suborbital rocket shares similar propulsion system and aerodynamical shape with a missile. A well-known example that proves the similarity is so-called “Norwegian rocket incident” caused by a Black Brant XII rocket launched from the Andøya Rocket Range to study aurora borealis over Svalbard. The rocket was detected by a Russian early-warning radar station and appeared to the station crew as a Trident missile. This caused full alert on Russian side and nuclear weapons were prepared to attack. Fortunately the mistake was detected (EUCOM History Office, 2012). In 2011 a rocket target based on Oriole rocket system was launched to simulate a missile attack as part of the Atlantic Trident military exercises (NBC News, 2011). Another example reported (Macdonald, 2016) is an American Terrier-Orion two-stage rocket which was launched from the United Kingdom in October 2015, and it was the first vehicle ever launched from the United Kingdom to reach the outer space. The rocket was launched to simulate a missile incoming to warships being exercised. According to press, the “missile” was successfully detected and shot down by the USS Ross. It was reported in press (defence24, 2019) that in 2019 a small suborbital test rocket developed by a Polish company Space Forest was detected and tracked by during testing campaign of a passive radar technology APART-GAS (Active Passive Radar Trials – Ground-based, Airborne, Sea-borne) on a Polish military ground.

2) Technology development and validation

As in the case of a technology validation for a space sector, safety & defense applications can benefit from the environment provided by suborbital rockets. Whereas in case of space sector a microgravity onboard the rocket is a widely used asset, it is the resemblance to actual missiles that proves useful in case of safety & defense applications. There are numerous examples of such tests, mostly from the United States. Sounding rockets enable tests of new missile systems components, such as sensors or releasing of simulating warheads for system tests (Martin & Law, 2002). An example of such flight is a Hypersonic Test Vehicle-2A flown for the US Department of Defense in 2010 (Federal Aviation Administration, 2011). A HOT SHOT in the USA programme, which included a rocket launch in 2018, aims to enable flight tests of missile systems onboard a relatively cheap flight vehicle, “filling a gap between ground tests and a final flight test” (Rummler, 2018). More recent example is a Terrier-Oriole launch carrying an experimental research payload for the Air Force Research Laboratory in March 2021 (Strout, 2021) – see Figure 3. The US Air Force has provided a grant to study using suborbital rockets to test materials, sensors and flight controls at hypersonic speeds (Reim, 2020). It is also speculated that a French V-Max vehicle demonstrating maneuvering during a hypersonic gliding would utilize a sounding rocket for its initial flight test (Trevithick, 2021).



Figure 3. Launch of a Terrier-Oriole sounding rocket, carrying an experimental research payload for the US Air Force Research Laboratory. Adopted from (*C4ISRNET, 2021*), Copyright 2021 by NASA

3) Peaceful utilization of surplus missile motors

Utilization of surplus military equipment, especially explosives and energetic materials is of major concern. Proper utilization prevents hazards and illicit transfers of weapons. Suborbital rockets often use surplus military motors as propulsion (NASA, 2019), and as such they contribute to safe utilization of surplus military materials. Example of such motors are Terrier MK12 or MK70 boosters (NASA, 2015).

4) Remote sensing

A report aiming to forecast a growth of suborbital flights' market (Tauri Group, 2012) predicts that suborbital rockets could be utilized for remote sensing purposes in military applications. Suborbital rockets could offer high resolution observations with swath widths with hundreds of square kilometers with an almost on-demand revisit time (provided the vehicles are available). They could ascend in friendly airspace and achieve views into hostile territory without violating airspace restrictions or exposing the vehicle to the treat of engagement. No actual flight demonstrations of this concept have been found in the literature review.

5) Other

There are more potential applications of suborbital rockets. For instance, aforementioned report (Tauri Group, 2012) foresees that price reduction of suborbital flights could result in new, unforeseen applications – especially military. It is worth noting that suborbital rockets use technologies and processes close to ones used in military rockets, regardless of their intentional usage. According to (NASA Sounding Rockets User Handbook, 2015), in the United States of America “Sounding Rockets are considered Significant Military Equipment (SME) and are listed on the ITAR US Muni-

tions List (USML)”. Safety procedures are required for any foreign national to be involved in experiment design and testing or field operations related to suborbital rockets

Requirements for a rocket to meet mission objectives can only be made for purposes number 1), 2) and 4). Purpose 3) – peaceful utilization of surplus missile motors describes how suborbital rockets can contribute to disarmament, and one could take it into account when designing a new vehicle (if one has access to such surplus motors). Purpose 5) is too general, however, it is noted that decreasing price may open new safety & defense applications. Main mission requirement for missile attack simulation purposes are to resemble a “real” missile in terms of radar cross section, trajectory, acceleration, speed, etc. – this requirement ensures that suborbital rocket used to emulate a missile will be “close enough” to an actual threat. This requirement is applicable to technology development and validation as well, as it also requires the suborbital rocket to resemble the missile – only this time it is a “friendly” missile. It is noted, however, that this requirement is strongly dependent on the missile one wants to emulate. Another requirement is that the suborbital rocket has to be much cheaper than an actual missile, otherwise it is not feasible and economical to introduce new type of rocket to tests. In case of remote sensing purpose, it is required to provide fine stabilization of the rocket during the observation. It is also desired to increase duration of observation, which probably means that capability to hover on high altitude would be desired.

4. Lukaszewicz Research Network – Institute of Aviation’s suborbital launch vehicles and related technologies

Lukaszewicz Research Network – Institute of Aviation is a research and development center dedicated to aeronautical and space engineering. Ł-IoA participates in European research programs which includes rocket propulsion projects for the European Space Agency. Projects involve development of aluminum-free solid motors for spacecraft deorbitation (Nowakowski et al., 2017a), hydrogen peroxide thrusters, bi-propellant engines for geostationary spacecrafts (Surmacz et al., 2017), throttleable rocket engines, and propulsion systems components such as catalytic beds (Surmacz et al., 2019), tanks (Gut, 2020) and valves. Ł-IoA has experience in development and utilization of sounding rocket systems. This experience includes both hardware and software used for design and development and for mission planning and safety analyses. Several rocket flight campaigns have been performed allowing the team to gain hands-on experience in safe rocket flight planning. Historically, 269 Meteor-family sounding rockets have been launched for technology development or atmosphere research purposes between 1963-1974. IoA was responsible for design and testing of the rockets and for launch campaigns’ preparation and execution. In 2019 IoA has performed a flight campaign of a cold launch demonstrator with gasdynamic reaction control system. In total 13 flights took place – most of them successful.

ILR-33 AMBER rocket is a technology demonstrator developed by Ł-IoA. The development process started in 2014 which included optimization efforts (Okninski, 2018; Okninski et al., 2018). The rocket is propelled by environmentally friendly hybrid motor with polyethylene as fuel and +98% High-test Peroxide (oxidizer), what makes it the first rocket utilizing HTP at such high concentration. Two solid strap-on boosters are used during the first flight phase (Nowakowski et al., 2017b). The first flight took place in 2017 at CSWL Drawsko. Two more tests took place in 2019, one in Drawsko (Pakosz et al., 2019) and second in Air Force

Training Centre Ustka (Okninski et al., 2019). The rocket render with all modules shown is presented on Figure 4.

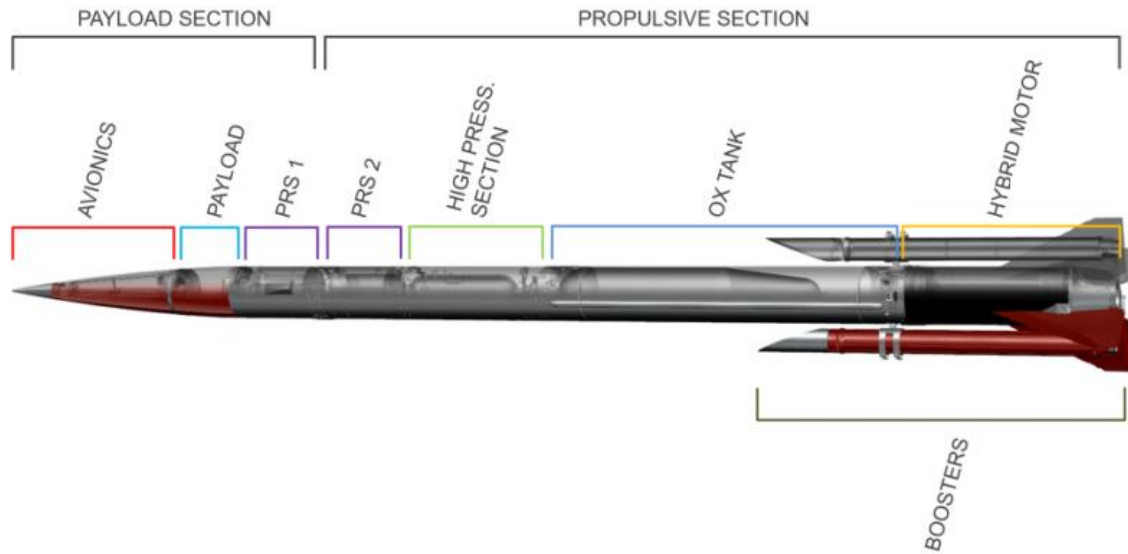


Figure 4. ILR-33 AMBER rocket. PRS 1 and 2 stands for – Payload Recovery System. A rocket configuration from 2017 with two recovery systems is shown. Own work of Ł-IoA.

Flight tests allowed to validate rocket's systems as well as ground infrastructure used during the flight tests. Altitudes of 15, 11 and 23 km were achieved, respectively. The rocket was able to reach altitudes of 60 km, however, the flight ceiling during all the three tests had to be limited due to legal reasons (limited airspace – 15 km) and safety aspects (small size of allowed impact zones, rocket dispersion increase due to the winds). Rocket velocity of 615 m/s, at Mach number 2.05 was achieved as the top value up to date. The maximum ascent acceleration was $\sim 12.5 g_0$. Photographs from the latest (at the time of writing) flight test are shown on Figure 5.



Figure 5. ILR-33 AMBER rocket flight test. Top-left – rocket’s ascent, note strap-on boosters still attached to the rocket. Top-right – the moment of strap-on boosters separation. Bottom-left – rocket in passive phase of the flight. Bottom-right – recoverable section of the rocket waiting for sea recovery. Own work of Ł-IoA.

The successor of the ILR-33 AMBER rocket is the ILR-33 AMBER 2K (Figure 6). The rocket is being prepared for a flight above the Kármán line with 10 kg of experiment. Due to the COVID-19 pandemic its first flight was postponed from 2020 to 2021. The rocket was also optimized with constraints to provide with at least 120 seconds of $10^{-4} g_0$ microgravity environment, to have a maximum acceleration of at most $15g_0$, a wet mass of below 300 kg and a 1σ impact point dispersion of no more than 20 km (Pakosz et al., 2020).



Figure 6. A rendering of ILR-33 AMBER 2K, a successor of ILR-33 AMBER rendering. Own work of Ł-IoA.

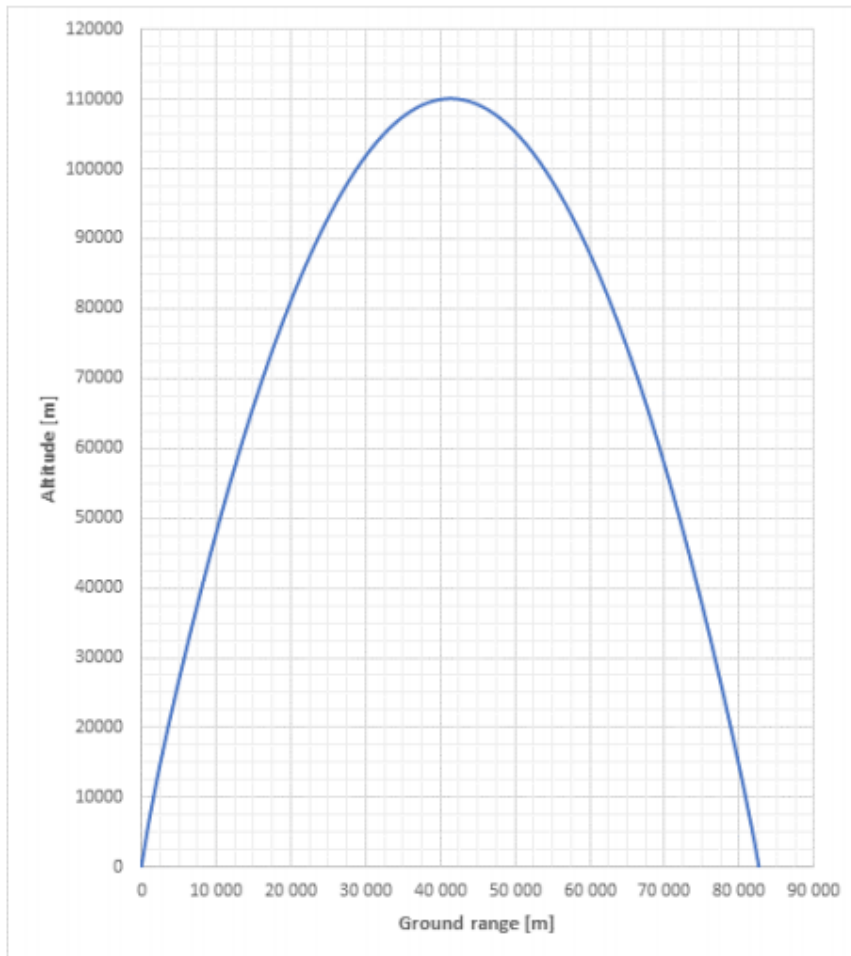


Figure 7. ILR-33 AMBER 2K trajectory. Own work of Ł-IoA.

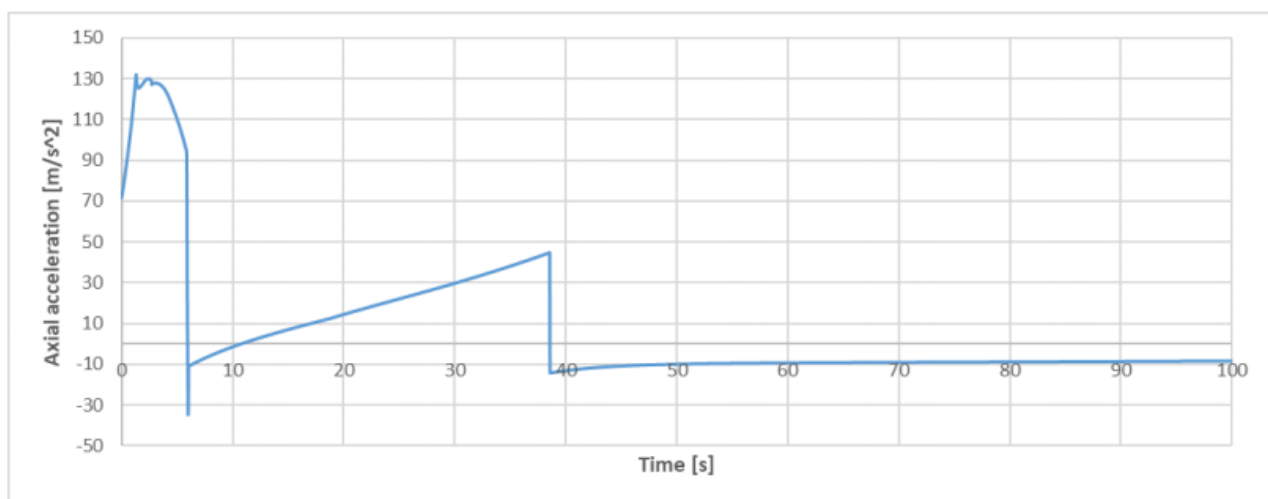


Figure 8. ILR-33 AMBER 2K acceleration profile. Own work of Ł-IoA.

Rocket’s trajectory and acceleration profile during the ascent are calculated using a 6 DoF simulation are shown on Figure 7 and Figure 8. Simulations show that the trajectory is resembling ballistic trajectories of missiles. In the simulated flight with hybrid motor delivering its full performance and launch pad elevation angle of 83° , the rocket reaches 110 km

apogee, and the distance from the launch pad to the impact point is 82 km. Acceleration of the rocket during its ascent is the highest shortly after launch and reaches over $13g_0$. When boosters finish thrusting and are ejected, the acceleration drops significantly and is then increased again until it reaches approximately $4.5g_0$ when the hybrid motor finishes thrusting. After that, the rocket is decelerated due to atmospheric drag and gravitational acceleration. The atmospheric drag is getting lower as the rocket ascends and microgravity conditions occur for approximately 2 minutes of the rocket's flight. The rocket in its current configuration is capable of achieving speeds above Mach 4 in a nominal flight.

5. Conclusions

Based on the study it is concluded that there are numerous use cases for suborbital rockets in the field of safety & defense. The most mature applications that can be offered by modern suborbital rockets are technology validation and missile simulation. There is potential for other mission types. ILR-33 AMBER 2K rocket has the capability to be used in safety & defense applications as it can mimic missiles for both technology validation and serve as a missile simulation to test air defense systems. Reaching high altitudes, Mach 4, high accelerations and having a ballistic trajectory it meets preliminary requirements for such applications. It is also relatively small sounding rocket and it has been cost-optimized. Its modular design will allow easy adaptation for various missions. Reaction control system is being developed that could stabilize the rocket during potential remote sensing (Noga, 2021). As pointed out in Section 3, mission requirements for safety & defense applications are highly case-specific. It is certainly part of the future work to attempt to simulate specific missions, i.e. to emulate a ballistic attack, however, such simulation should include data regarding the missile to be simulated, which is not publicly available.

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