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Development of a Suborbital Inexpensive Rocket for Affordable Space Access

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Abstract

The Suborbital Inexpensive Rocket (SIR) project will introduce to market a suborbital launch vehicle by the name of "PERUN", currently under development, with an expected maiden flight in 2019. Powered by a hybrid rocket engine using green eco-friendly propellants (Paraffin/N2O), PERUN in its standard configuration will have the capability to carry 50 kilograms of scientific payloads to an altitude of 150 kilometres and return them safely. Following a very precise actively controlled and guided flight, PERUN is intended to deliver its payload to the desired altitude and use its recovery system to land back softly in an autonomously controlled manner, allowing the rocket to be fully reused, lowering the costs of manufacturing, operation, and recovery. With a launch manifest up to two flights per month, PERUN will be a solution to a problem that is affecting the space market: it is underserved by all active suborbital rockets which are more expensive and dedicated for higher altitudes. As a cost-effective launch vehicle, PERUN is expected to offer its service for prices four times lower than the cheapest in the market. This will fill the gap in the suborbital launches market, allowing more exoatmospheric astronomical research, weather monitoring, short duration microgravity research experiments, hardware flight testing, and will encourage the engagement of more entities to the field of space research and exploration. The flight profiles, mission design, payload handling conditions, general designs, analysis and proposed operations are discussed in this paper with the upcoming steps and future work. The procedure meant to be taken in the upcoming project stages to make the vehicle user friendly and easier to adjust to the experimenter's needs is briefly introduced.

Keywords: Hybrid propulsion, Suborbital space, Small launchers, Reusability

Acronyms/Abbreviations

SIR	Suborbital Inexpensive Rocket
SF	SpaceForest
TRL	Technology Readiness Level
ADCS	Attitude Determination and Control System
MSL	Mean Sea Level
TEL	Transport Erector Launcher

1. Introduction

SpaceForest is a European space company providing various services to facilitate the commercial and scientific access to space. Our Experimental Rocket Department is focused currently on carrying out the Suborbital Inexpensive Rocket (SIR) project to develop the PERUN rocket. The aim of this project is to develop a fully reusable suborbital rocket capable of carrying around 50 to 75 kg of payload to an altitude range of 150 to 225 km.

PERUN, illustrated in Fig. 1 and 2, is designed to be ideal for providing high performance and reliability at low cost for suborbital space users. PERUN will be a single-stage guided suborbital launch vehicle; it will be flight proven in 2019 and will be active to serve the market starting in 2020.

The rocket has two configurations; reusable and expendable. 90% of the rocket's main components are designed to be reused for 4-5 flights without the need to be refurbished and with a turnaround time of 36 hours.

PERUN will have an estimated lift-off weight of 950 kg in its standard reusable configuration and will stand at an overall height of 10 meters, with a diameter of 45 centimetres. The rocket is meant to be fully reusable with a very short maintenance and inspection time span between flights to offer a fast launch manifest.

Fig. 1. Artist concept of PERUN

Fig. 2. PERUN suborbital rocket CAD model

The rocket offers various advantages over other active rockets in its category such as:

- Controlled flight path
- Trajectory accurate determination
- Controlled ascent accelerations
- Controlled descent and re-entry orientation
- Simple on-pad preparations and transportation
- Simple pre-launch operations
- Fast payload integration

Before the final flight version of SIR is complete, a demonstrator version is being developed and is to be flight-tested by the end of 2019 to verify various design points and reach operational maturity of the subsystems. This demonstrator will be powered by a 1:5 scaled hybrid engine, SF200, which is a development step for the SF1000 engine [1].

PERUN's mission is to deliver its payload to a specified altitude, often to provide a long-lasting and high-quality microgravity environment for experimental testing. This makes the main goal of the rocket subsystems and mission design teams to maximize the payload capabilities of the rocket and improve its range and performance. The flight events are illustrated in Fig. 3 and detailed in Table 1.

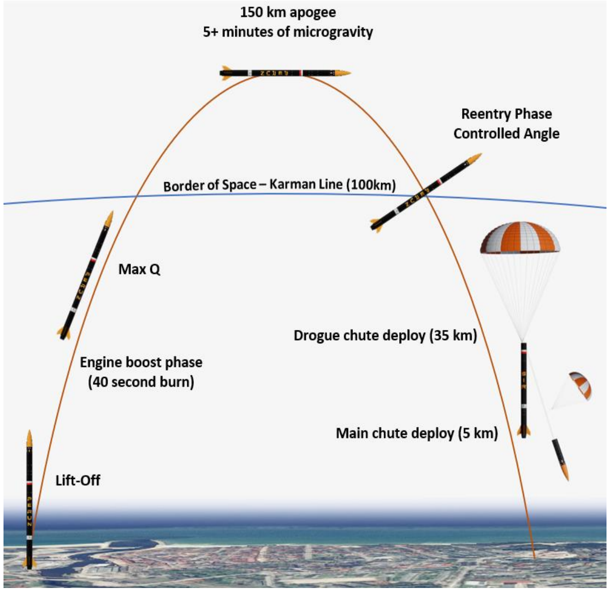

Fig. 3. PERUN suborbital flight events

The avionics, ground station, and communication modules of PERUN are being developed and tested to fit latest technologies and to be able to accommodate and serve nearly all the sizes and type of suborbital experiments in the market. Payload servicing modules will be introduced with a range of capabilities to suit the market needs, including access to space or ejection into space.

Table 1. Preliminary list of flight events of PERUN

	Time (s)	Approx. altitude MSL (km)
Engine ignition	0	0
Max Q.	25	28
Engine shut down	40	36
Apogee	195	150
Re-entry control start	325	80
Drogue chute deploy	450	35
Main chute deploy	800	5
Touchdown	1700+	0

2. Concept and methodology

The SIR project will introduce new technologies to the space field. The usage of hybrid rocket engines to power a suborbital launch vehicle is a relatively new approach, not widely used for space launch vehicles. It offers high operational performance while maintaining low costs and high standards of safety for launched missions.

The usage of paraffin wax as fuel for the hybrid rocket engine is one of the most recent advantages in our hybrid propulsion developed technologies. Paraffin wax is an inexpensive, safe, and efficient fuel. Alongside the usage of green propellants for hybrid propulsion which at high operational efficiencies effectively reduce the negative impact of the launch operation on the environment.

Additionally, PERUN is designed to use a precise ACDS to guide the rocket back to land at a certain location, avoiding most of the operational costs of recovery and dramatically increasing the rocket's mission safety and reliability. The ACDS utilises a cold gas thruster to maintain a guided flight path and facilitate accurate recovery.

Currently the technologies and research stand at TRL 6. The technologies being developed currently at SF will be implemented into the design cycle and preliminary considerations and review till the point to be integrated in PERUN to reach TRL 9.

3. Market analysis

The global dependency on orbital means of accessing suborbital space became clearly noticed recently. This is due to an increase in the pace of development of space related R&D activities and experiments that require a micorgravitational space environment to be tested. This dependency adds a huge burden on institutes, both industrial and academic, whose work needs to be launched and tested in such an environment.

This creates huge obstacles starting with expensive costs, complexities of transportation, assembly waiting time, logistical problems, and delays in time schedule due to usually being a secondary payload. With the market witnessing all this evolution, towards nano and micro satellites as well, the dedicated small launchers appear to be needed more than ever before [2, 3].

PERUN will be serving an altitude range which is the target for many small and medium space experiments. Such altitude range is unserved by the current means of space transportation, which forces those experiments to take place in orbital rockets meant to serve higher altitudes.

This increase in costs makes the existence of PERUN a necessity for the space industry, and the SIR project will encourage the engagement of more entities to the field of space research and exploration. This project will not only involve building the hardware for PERUN, but will also provide a full feasibility study alongside a business market development plan in which several related difficulties and solution scenarios will be assessed. SIR project delivers a complete launch service to the market including:

- Launch vehicle operation
- Payload integration
- Payload interfaces for power supply
- Late access to payload before flight
- Payload recovery
- Flight performance report

4. Rocket preliminary overview

PERUN will be powered by the SF1000 nitrous oxide/paraffin-based hybrid rocket engine will have no less than 1 MNs of total impulse, powering the rocket to the capability of carrying up to 75 kg of payload. During a nominal standard mission, the payload will be carried to an apogee of 150 km. Reducing the payload weight will result in an increase in apogee. Table 2 illustrates PERUN's performance specifications in its standard configuration.

Besides the very low cost per flight, PERUN is a simply designed rocket which allows for late access to the payload section: up to 30 minutes before lift-off. This offers the chance for special payloads (e.g. biological experiments) to be installed on-board the rocket soon before flight.

This flexibility is due to having a safe propulsion module whose tanks are filled in a simple and timely manner at the very last phase of ground operations. Human presence for payload preparations around the rocket and on the launch pad will be at a high safety level due to these facts.

One more advantage of PERUN's services to the market is that its hybrid rocket engine allows throttling and thrust control, which makes it adaptable to experimenter's needs in terms of acceleration, velocity, and altitude. This gives an essential advantage as rockets using solid propulsion cannot control their thrust and cannot offer such service options. This is an important point for any user, making PERUN a rocket of unique capabilities and of great benefit to the market.

Table 2. Performance specifications of PERUN

Function	Suborbital launch vehicle
Manufacturer	SpaceForest
Price	< $4000/kg
Height	10 m
Diameter	0.5 m
Dry mass	325 kg
Wet mass	950 kg
Stages	1
Payload	50 -75 kg
Acceleration	Adjustable to customer needs
Propulsion system	Hybrid
Fuel/oxidizer	Paraffin/Nitrous oxide
Burn time	40 s
Engine control	Throttleable (25-100%)
Flight control	Cold gas ADCS
Recovery control	Drogue controlled parachute
Recovery system	Dual deployment
Launch site	Andoya SC/Esrange SC

5. Rocket subsystems

PERUN is divided in 8 main subsystems which are independent of the mission or specific payload, to cover the 6 main roles that guarantee the successful operation of the rocket:

- Propulsion
- Aerodynamics
- Structure
- Communication and telemetry
- Electronics and instrumentation
- Payload servicing.

These sections according to the preliminary design are shown in Fig. 4 and described in Table 3.

Table 3. List of PERUN rocket subsystems

1	Propulsion module
2	Propellant storage and feed module
3	Recovery module
4	Payload modules
5	Communication module
6	Guidance module
7	Avionics & instrumentation module
8	Airframe

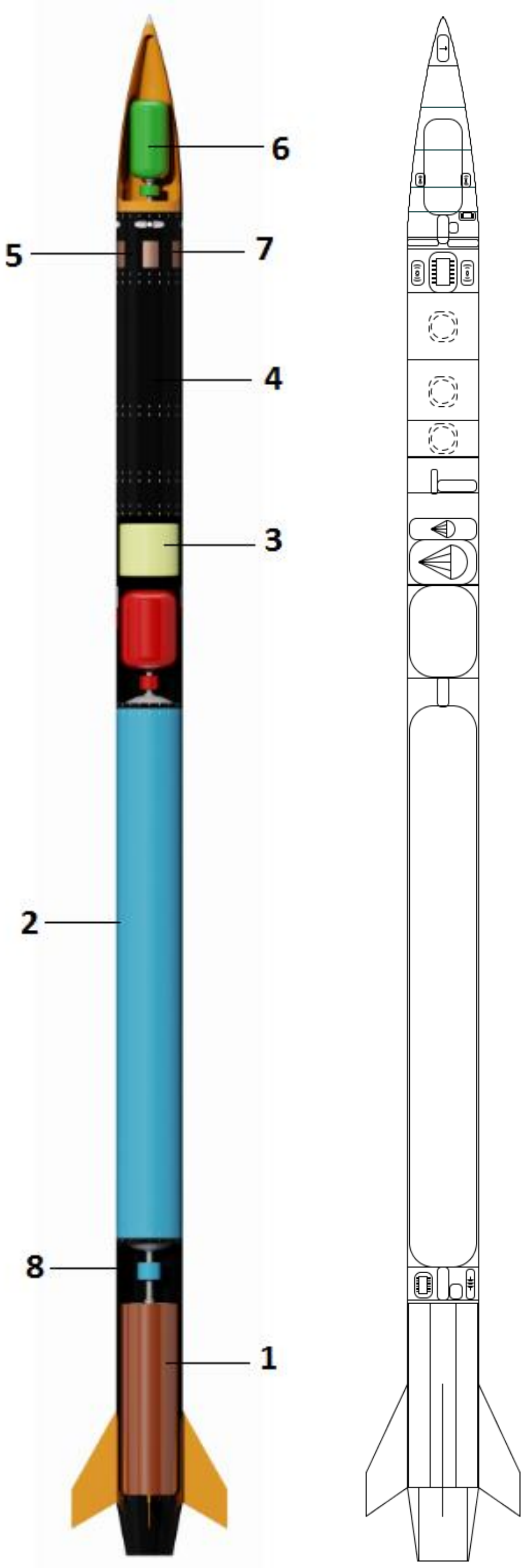

Fig. 4. CAD and schematic models of PERUN

5.1 Propulsion module

The rocket will be powered by the SF1000 hybrid rocket engine. SF1000 uses nitrous oxide as oxidizer and a paraffin-based composition as fuel. There are many advantages of using hybrid propulsion: offering wide range of throttleability; usage of a green, storable oxidizer; simplicity compared to other propulsion systems; and low cost of operation and development [4].

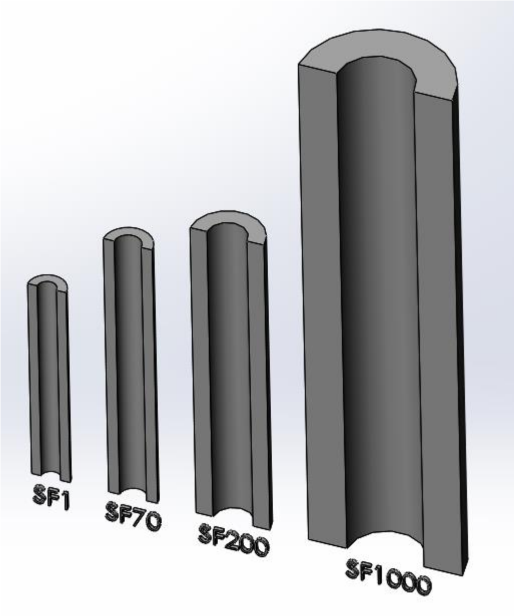

Fig. 5. Comparison of SF hybrid engine fuel grains

The SF1000 development program started with three main subscale models of the engine: SF1, SF70, and SF200, shown in Fig. 5, alongside with a series of lab-developed test engines. The engines were used to demonstrate the technologies and illustrate the capabilities of the SF rocketry department to master hybrid rocket propulsion research and development technologies. Fig. 6, 7 and 8 shows different tests of the SF hybrid rocket engines family.

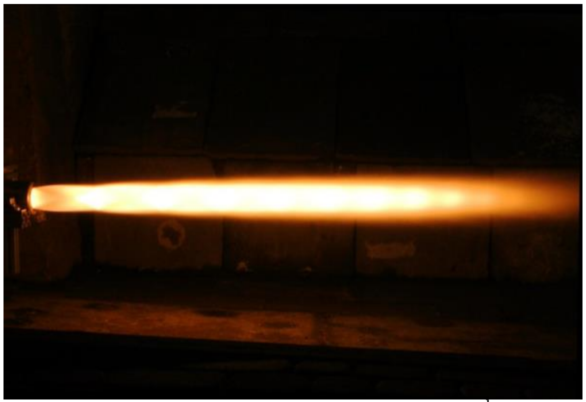

Fig. 6. SF1 hybrid rocket engine, 33rd test

Fig. 7. SF70 hybrid rocket engine, 9th static test

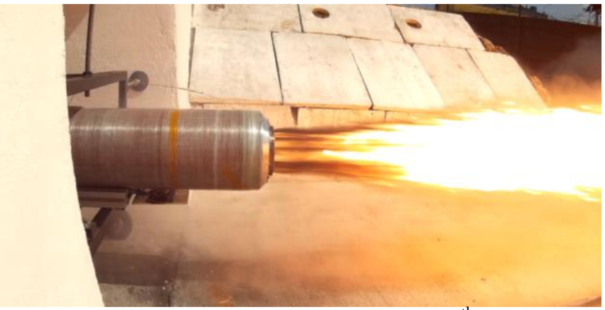

Fig. 8. SF200 hybrid rocket engine, 4th static test

5.2 Propellant storage and feed module

The propellant storage and feed module mainly host the oxidizer tank, pressurant tank, and the main feed system valves and sensors. The oxidizer tank will be filled with around 500 kg of nitrous oxide needed for the engine operation, and will be made of carbon-composite to reduce the overall dry weight of the rocket.

The pressurant tank is to be filled with compressed inert as to pressurize the oxidizer tank throughout the engine operation. A full investigation is being conducted to determine the need of the pressurant subsystem for the performance of our flight engine and to choose the proper pressurizing gas.

5.3 Recovery module

SpaceForest is developing its own recovery system and manufacturing its own parachutes in-house. This reduces the costs and added compatibility of the products for the required mission. Parachute development at SF is a process that has a strong heritage, as shown in Fig. 9, based on the experience of a talented team. The design, assembly, testing of the recovery system alongside the separation system will be conducted in-house as well.

The recovery system of PERUN is one of the main subsystems that guarantee the successful operation of the project. Following the reusability concept, the rocket is to be guided back using controlled parachutes to land within the predetermined landing zone. This requires the design and manufacturing of the recovery system to be flawless in order to guarantee successful operation of the rocket.

Fig. 9. Parachute deployment for the BIGOS 3 rocket developed by SF

The recovery system of PERUN depends on a dual deployment system, shown in Fig. 10, that operates with a drogue parachute to decelerate the rocket at the beginning of the recovery system operation. The separation subsystem of PERUN is included within the recovery system; it is operating to gently eject the nose cone with the payload bay releasing the drogue, later followed by the main parachutes.

The flight computer is responsible for the separation and initiation of the parachutes opening. The main parachute is designed to open at an altitude less than five kilometres to reduce the effects of side winds and provide more control authority over the rocket.

Fig. 10. PERUN parachute dual deployment rendering

5.4 Payload modules

The main function of PERUN is to deliver the customer's payload into the designated altitude. SF offers three different payload bays, shown in Fig. 11 and 12, each will be provided to the customer to attach the payload and send it back to SF for integration before flight. Mounting inside the modules can be customized or payloads can be attached to a standard isogrid pattern. Each module will be sealed airtight, individually, to stay pressurized during flight, if necessary for customer specifications.

Fig. 11. CAD model of the payload modules of PERUN

Payloads can be kept in climate-controlled storage conditions, including during transportation to the launch site, and will be supplied power if necessary, throughout this time. Prior to oxidizer tank filling, about 30 minutes before launch, access to payloads from a horizontal rocket position will be possible. Payload integration and assembly will be done by SF, alongside providing complete support to the payloads in terms of servicing (power, communication) and flight performance reports. Preliminary options of PERUN are illustrated in Table 4.

Fig. 12. CAD model of the payload section integration

Table 4. Preliminary payload options of PERUN

Allowable payload specs.	PM-1	PM-2	PM-3
Height (mm)	200	350	450
Diameter (mm)	400	400	400
Weight (kg)	12.5	17.5	25
Access door	2	2	3
Access to space	No	No	Yes
Ejection to space	No	No	Yes

5.5 Communication module

The long-range communication between a suborbital rocket and a ground station requires use of specific antennas and radio modules in order to make reception of the signals possible. In order to maximize the range, high gain antennas are preferred, however, high antenna gain results in narrowing of radiation patterns, which in the case of a rocket might be unfavourable due to rotation of the rocket during its flight. To achieve the highest possible visibility, a ground station, shown in Fig. 13, including a high gain antenna and a rocket terminal using a moderate or low gain antenna is to be used.

Fig. 13. RASEL 1 ground station developed by SF

5.6 Guidance module

To assure the highest levels of professionality and to improve the performance and quality of its flights, PERUN, being a fully-controlled rocket, will introduce this new aspect to the suborbital market. Micro-gravitational research usually requires specific needs in terms of acceleration, velocity, roll rates, and altitude. These needs can be fulfilled with a launch vehicle able to offer the option of a completely controlled and guided flight.

PERUN is equipped with two different guidance modules that work together to fulfil guidance requirements: a set of canards and a cold gas propulsion system. The canards are composed of a set of active stabilizing fins, scaled model shown in Fig. 14, to control the rocket's trajectory and orientation while operational within the atmosphere.

Fig. 14. Canards guidance module developed by SF for the scaled model of PERUN demonstrator rocket

The cold gas propulsion system is being developed to offer control authority of the rocket at higher altitudes in which there is not enough presence of air to use the canards efficiently [5]. The usage of cold gas thrusters will also offer the ability to control the precise altitude and orientation of the rocket once it enters the region for micro-g experimentation.

5.7 Avionics & instrumentation

The avionics of PERUN, represented by the main flight computer shown in Fig. 15, control all of the rocket maneuverers and operational functions, during and post flight. Besides controlling the flight trajectory, supporting the payloads with the needed power and data storage are the main functions of the avionics and instrumentation module of PERUN. The module is equipped with power storage in the form of batteries and a power distribution system that serves the whole rocket and the payloads.

Fig. 15. Avionics module developed by SF for the scaled model of PERUN demonstrator rocket

The different types of instruments and sensors on-board PERUN not only contribute to the control loops of the rocket but also provide the ground station with all the required data to monitor and analyze the rocket before, during, and after its flight. The avionics of PERUN are developed in-house by SF and are tested completely prior to each flight.

Work developing the main flight computer, the avionics, and instrumentation of PERUN includes developing the payload servicing and storage module.

5.8 Airframe

The rocket frame and structure will be designed and manufactured to withstand the high loads of flight and landing. The frame of PERUN will be wound in-house and composed of ultra-light carbon composite materials to reduce its dry weight. SF is actively increasing its composites capabilities so that all necessary custom parts can be manufactured to precise tolerances and high strength. The main components for the structure of the rocket as well as the boattail and fins are as well will be made of light-weight composite laminates.

6. Mission design

The mission design of PERUN starting from payload contracting, flight path directory, and launch management are done by a talented team with more than 8 years of hands-on experience.

The flight path of PERUN follows a profile of a suborbital trajectory controlled by an active control system on board of the rocket. The momentum along the trajectory sustains the rocket to achieve the desired altitude at a chosen orientation and offers more than 5 minutes of microgavitational space experience.

The mission schedule timeline for a launch is at a fast and cost-effective pace to facilitate transportation and assembly of payloads on the rocket. Launch requests for a payload to be on-board PERUN can be as short as 10 days before launch. Payload updates and maintenance can be done up to 30 mins before lift-off which offer great flexibility for customers and users.

6.1 Lift-off and engine burn phase

PERUN is powered by a hybrid propulsion system which will support enough thrust to push the rocket to the designated altitude. During the engine burn phase, the rocket will coast along a predetermined trajectory optimizing the usage of its fuel. This is done using its throttleable engine characteristic which offers a great advantage in controlling the acceleration of the rocket and reducing fuel consumption.

6.2 Active stabilization system

The ADCS is based on the usage of the cold gas thruster to control the rocket's altitude and orientation in space [5]. Such a system is considered an optimum solution to provide small launch vehicle with control authority and improve its performance. The system utilizes nitrogen as propellant providing the thrust needed to guide the rocket during ascent and re-entry.

6.3 Space and Micro-g time

The ADCS will be used to guarantee reaching the desired precise altitude following a pre-determined trajectory. Once reaching space it will orient the rocket according to the experiment's requirements to allow a wide aspect of choices of simulated conditions for customers. PERUN can be precisely controlled to facilitate the longest time of high-quality microgravity possible.

6.4 Re-entry

PERUN will start its re-entry procedure to dissipate the energy acquired from its trip to space in a way that will guarantee neither high loads on the payloads carried nor damage to any of the rocket parts. This will increase the life span of various parts of the rocket, enabling reusability of them.

The recovery system will be initiated in the sequence of dual deployment. A drogue parachute will deploy first to slow the rocket descent rate. This drogue is controlled to glide allowing the rocket to reach the landing zone parameter. Before touchdown the main parachute will deploy to slow the rocket to its landing velocity allowing a soft impact on the rocket upon touchdown.

7. Launch operations

7.1 Launch system

For developers of suborbital rockets and small-lift launch vehicles, launch location and architecture, and cost can be of great concern. Many costs are associated with the rental of launch-site utilities and personnel necessary to set up systems specific for each rocket or each launch, often requiring long-distance transportation, and limited numbers of launch locations.

Our engineers decided to use a transport erector launcher, as the TEL can allow for ease of transportation and flexibility of launch site usage at the same time.

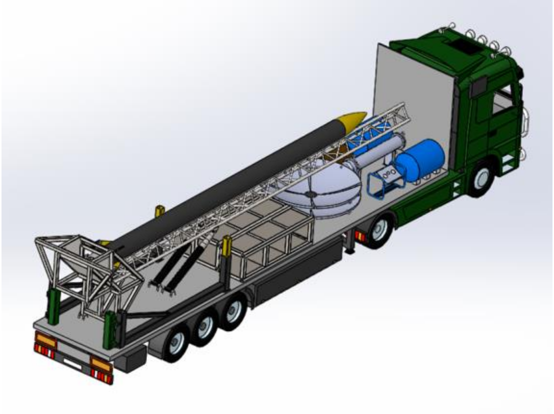

Fig. 16. CAD model of the TEL attached to its truck

Using an erector system simplifies and expedites the assembly of the rocket, by providing a horizontal work space more easily accessible to working hands, and reducing the assembly time at the launch site and its facilities [6].

A system such as this can lead to more rapid testing, development, and launching, following the unwritten standard of new space companies to push the envelope on new technologies, ideas, and strategies faster than before.

Fig. 17. Rendering of the TEL during transportation configuration

Fig. 18. Rendering of the TEL in its launch configuration

The TEL, as shown in Fig. 16,17 and 18, is typically a trailer fitted for the purpose of transporting the rocket, erecting it, and launching it all from the same system. This often implies the rocket is already being transported on its own combination launch rail/strongback. The system at SF will incorporate hold-down clamps at the base of the PERUN as well as an exhaust deflector as part of the rotating strongback structure. Located just below the motor, the hold-down clamps will be hydraulically actuated to retract from the rocket body at the time of launch after assuring lift-off command. The strongback clamps will also be used to secure the rocket during transportation and erection.

7.2 Launch sites

Fig. 19. Proposed launch sites for PERUN's test flight

The main launch sites for PERUN are based in northern Europe, as shown in Fig. 19, with the capability to be launched from various different locations thanks to the TEL. Esrange Space Center and Andoya Space Center are both working in cooperation with SF for the preparations and launch of PERUN. The launch campaign is coordinated with either launch site based on customers' preferences and is completely carried on by SF. The ability to launch from northern Poland is currently being negotiated, and due the proximity SpaceForest's headquarters, launch costs and therefore payload costs could be substantially reduced.

8. Conclusion

The Suborbital Inexpensive Rocket (SIR) project, by introducing PERUN to the suborbital market, will contribute widely to the progress, enthusiasm, and development of global space and scientific initiatives. PERUN, as a reusable hybrid engine-powered suborbital rocket, will be dramatically lower in cost than all current suborbital launchers, due to the simplicity in engine and subsystem design, efficient in-house manufacturing and testing, and the inclusion of efficient launching strategies. The effect of this will allow more payloads to be launched, tested, and certified in a space environment, especially in the micro-gravitational experimentational fields of scientific studies and research. The low costs per kilogram will be especially attractive to universities and companies alike suffering from monetary constraints, but wanted to test payloads and hardware.

Over the next year, subsystem and engine testing will be extensively performed to give proof of concept and increase customer confidence, before the first full-scale demonstrator launch in 2019. After finishing the plan for development and testing, PERUN will offer at least 12 flights per year for customers with a very low waiting time between submitting a launch request until the actual launch and payload recovery. With more flight orders the launch manifest of PERUN is able to be increased yearly. This low-cost, high-volume model of business is an absolute necessity to meet the increased demand in the space industry, which is only just beginning to flourish. PERUN will push the envelope for what is possible in terms of safety, reliability, reusability, cost, and volume of flights in this quickly growing and evolving space industry.

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