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Hybrid Sounding Rocket HEROS: TRL 9

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Abstract

The inherent safety of hybrid rocket propulsion offers some unique advantages compared to solid and liquid propellant rocket engines. This makes it especially attractive for space tourism, Micro-launcher and hands-on experiments in the education of students. On November 8th, 2016 at 10:30 a.m. the hybrid sounding rocket HEROS 3 was launched from the ESRANGE Space Center to an apogee altitude of 32,300 m (106,000 ft). This set a new altitude record for European student and amateur rocketry and a world altitude record for hybrid rockets built by students. The 7.5 m long rocket is using Nitrous Oxide (N_2O) and a Paraffin-based fuel to produce 10,000 N of thrust. The dry mass of the rocket was only 75 kg thanks to a carbon fibre structure for the most part. The rocket performed the record breaking flight at perfect weather and visibility conditions, reaching a maximum airspeed of 720 m/s and Mach 2.3. The rocket performed a soft landing with two parachutes and can be reused. Flight data and engine performance data are published and analyzed. The flight data shows excellent stability of the rocket. Engine performance data proves very high efficiency and stable combustion as in the ground tests. Engine and flight trajectory simulations show very good agreements with the flight data. Furthermore, the overall project, the rockets design as well as the launch campaign are presented here in detail.

1. Introduction

Hybrid Engine Development (HyEnD) is a student based project located at the University of Stuttgart, founded in 2006. In the years from 2006 to 2012, HyEnD focused on developing its own hybrid rocket engines in different scales from 250 N to 2000 N thrust[29]. In 2012 the project Studentische Experimentalraketen (student experimental rockets) STERN[36] was initiated by the German Aerospace Center (DLR) and HyEnD applied for it with the Institute of Space Systems. The experience and knowledge of HyEnD in developing and testing hybrid rocket engines was the foundation to develop, construct and build its own experimental hybrid sounding rocket within the planed three years of the STERN project.

In September 2012 the rocket development began, starting from scratch. The previous experience with hybrid rocket engines was the basis for the project. Within the first year, the concept of the rocket HEROS (Hybrid Experimental ROcket Stuttgart) was developed. Simultaneously, a smaller demonstrator rocket, MIRAS, was initiated in order to test all subsystems in a smaller scale before the launch of HEROS in 2015. HEROS was targeted to have a thrust of 10 kN and an to reach altitude of more than 20 km. A smaller scale was applied for MIRAS, which reaches altitudes of around 2 km with a 500 N engine. This allows test flights of the rocket on German launch sites. Both MIRAS and HEROS use a hybrid rocket engine with a paraffin-based fuel and liquid N_2O as oxidizer. More than 150 hot-fire tests have been performed in the HyEnD project so far. Results of the 500 N engine development are presented in[40] and the 10 kN engine is presented in[33]. The design of the HEROS hybrid sounding rocket is presented in detail in[43]. A lot of improvements were made to the design of the different subsystems during the development of the MIRAS demonstrator, which were applied to the HEROS rocket design until the end of the 2nd year. At that time, HyEnD also passed the Critical Design Review. The review board included experts from the DLR MORABA, the DLR Space Agency and the DLR Institute of Space Propulsion. Six reviews have been passed in total during the project. In early 2015 the MIRAS demonstrator rocket was launched successfully, proving that the baseline concept is working. In summer 2015 a 2nd flight of MIRAS was done before the launch campaign of HEROS in October 2015. All HEROS flights took place at the European Space and Sounding Rocket Range (ESRANGE) near Kiruna, Sweden. A project timeline is given in Table 1. The first launch of HEROS 1 in October 2015 ended prematurely due to combustion instability and a burn-through of the combustion chamber. Low temperature N_2O was the cause of the failure. However, a project extension

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for one year for a failure analysis was granted. After the successful Failure Analysis and review, it was decided to build and launch the slightly improved rockets HEROS 2 and 3. Next to the engine, more improvements were made with an advanced on-board measurement system, a new telemetry system and power control unit[32].

Table 1: Timeline of the HyEnD-STERN project at University of Stuttgart

Date	Event
Jun. 2006	Foundation of HyEnD
Jul. 2008	First Hybrid Rocket Engine Test Campaign
Sept. 2012	Begin of STERN project funding
Sept. 2013	Begin of MIRAS 500 N engine Test Campaign
Dec. 2013	**Preliminary Design Review**
Nov. 2014	Begin of HyRES 10000 N engine Test Campaign
Nov. 2014	**Critical Design Review**
Feb. 2015	1st launch of MIRAS
May 2015	**Integration Progress Review**
Aug. 2015	2nd MIRAS launch
Sep. 2015	**Rocket Acceptance Review**
Oct. 2015	**Flight Readiness Review**
Oct. 2015	HEROS 1 launch
Nov. 2015	Post flight analysis
Apr. 2016	Project Extension
Jun. 2016	**Failure Analysis Review**
Jul.-Sep. 2016	Assembly of HEROS 2 and 3
Oct. 31st 2016	HEROS 2 launch
Nov. 7th 2016	ESRANGE Safety Board: Go for launch
Nov. 8th 2016	HEROS 3 launch

2. State of the Art of Hybrid Rocket Propulsion

2.1 Liquefying Hybrid Rocket Fuels

Hybrid rocket engines have distinct advantages[2,35,44] compared to classical solid[8,9] or liquid propellant rocket engines[41,48]. The interest in hybrid rocket engines is quite high, which is indicated by the number of publications during the last years. In comparison to solid rocket engines, their TNT-equivalent of zero offers huge safety advantages during storage and handling. These advantages lead to reduced total costs of such a hybrid rocket engine. Controllable thrust including shut off and restart capability are further advantages. Less pipings and valves due to only one liquid component introduce less complexity and reduced costs compared to liquid rocket engines. Applications especially in space tourism like SpaceShipOne some years ago clearly show the potentials of hybrid rocket engines. One of the disadvantages might be the use of polymeric fuels. These fuels, like Hydroxyl-terminated Polybutadiene (HTPB) or High-Density Polyethylene (HDPE), show relatively low regression rates, which results in the necessity for multiport fuel grains for high thrust applications. The multiport design increases the residual mass of unburnt fuel and thereby decreases the delivered specific impulse. Instabilities are also more likely with this type of design.

Liquefying hybrid rocket fuels were investigated in the last years. Cryogenic solid n-pentane showed regression rates 5-10 times higher than polymeric hybrid fuels[7]. Following these studies, tests were done at Stanford University with long chain hydrocarbons that are solid at ambient temperature[17,20]. These fuels are Paraffin-based and show a 3-5 times higher regression rate than polymers at similar mass fluxes. This is achieved by a different combustion mechanism. Paraffin fuels form a liquid layer on the fuel surface during the combustion[20]. It is expected that the low viscosity and low surface tension of the liquid fuel enable an additional mass transfer by entrainment of liquid droplets. The gas flow over the surface induces liquid layer instabilities, which produce the droplet entrainment[21]. The classical hybrid boundary layer combustion was analyzed already around 1960, also with Schlieren imaging[37,52]. Recently this technique was also applied to liquefying hybrid fuels[15,28]. Optical results of the entrainment process of low viscosity liquefying fuels are shown in detail in[34,38]. Novel, automated data evaluation techniques to characterize frequencies and wave-lengths of the entrainment process are presented in[34,39]. Scale-up tests were done and confirmed that the theory is also applicable for engines at larger scale[25]. Recent tests with different Paraffin-based fuels and Gaseous Oxygen showed an exponential relation between the liquid layer viscosity and the overall regression rate[30,31].

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Numerical analysis of the liquid layer instability was done in[1] .

2.2 Recent and Current Programs

Hybrid rocket engines are in the focus of research at several institutions and universities world-wide. They are well suited for educational purposes with students due to their aforementioned inherent safety. Especially small-scale combustion experiments are widely available and described in detail in the literature. At larger scales, the number of experiments and available data is much smaller. Their good performance, depending on the chosen propellant combination, makes hybrid rockets attractive for sounding rockets and Micro-launcher. The throttling and restart capability are further advantages of hybrid rocket engines.

The biggest operational hybrid rocket engine was realized within the Hybrid Propulsion Demonstration Program in the United States[47] . The engine was based on HTPB and Liquid Oxygen (LOX) with a thrust of 250 klb. Sub-scale tests were successful while the full thrust engine still suffered from instabilities. Different flight tests have also been performed, with exception of SpaceShipOne, mostly with problems[46] . Recent efforts from NASA Ames, the Stanford University and the Space Propulsion Group Inc.(SPG) were aiming at developing the Peregrine sounding rocket in a joint program. It uses a hybrid rocket engine with N_2O and a Paraffin-based fuel to launch a 5 kg payload to an altitude of more than 100 km[10] . The development of the engine was challenging due to the occurrence of low frequency instabilities based on feed system coupling and acoustic instabilities[53] . The low frequency instabilities were partially related to the injection conditions of the N_2O, especially its vapor pressure[50,51] . The latest tests showed stable operation at high efficiency. In the last years, SPG developed a high performance hybrid rocket engine with LOX and Paraffin-based fuels as propellants[24] . Its application was proposed as an upper stage engine with an extrapolated vacuum specific impulse of 340 s. The technological challenges of combustion instabilities, which often arise with LOX hybrid rocket engines[27] , were said to be solved only by advanced combustion chamber and injector design and passive devices. These instabilities were only solved partially in previous engines by injecting pyrophoric liquids, which increased the complexity and decreased the inherent safety of hybrid rocket engines[3,4,18] . Often low-frequency instabilities can arise in hybrids[22] which are based on a coupling between thermal transients in the fuel grain and transients in the boundary layer. The JAXA in Japan is investigating a wide field of different hybrid rocket propulsion concepts[45] . This includes the work on a 5 kN swirling oxidizer flow hybrid rocket engine[42] . SpaceShipOne and SpaceShipTwo are still the most well-known examples of flight tested hybrid rocket engine applications. A sub-orbital hybrid sounding rocket is in development by the Norwegian company Nammo[5,49] . The engine is using a HTPB fuel and Hydrogen Peroxide (H_2O_2) as oxidizer. The Jet Propulsion Laboratory is evaluating hybrid rocket propulsion as a technology for a Mars Ascent Vehicle[26] . It shall use a wax-based fuel formulation from SPG, which has a lower glass transition temperature than HTPB and a wide operating temperature range from -100 °C till 50 °C[11] . Thereby, it is attractive for this application on the Mars where high temperature variations on the surface exist.

3. HEROS Key Technologies

The sounding rocket HEROS is shown in Figure 1. Its main dimensions, components and subsystems are shown in Figure 2. In addition to the rocket systems, a lot of work and effort has been invested in the Ground Support Equipment (GSE). It was used at ESRANGE to load or unload the oxidizer, supply the rocket with power while on launch pad, operate the on-board electronics, the cameras and provide a remote connection to the control room at the launch site.

Stable and efficient combustion in the rocket engine is mandatory for a sounding rocket that shall reach high altitudes. A hybrid rocket engine was chosen due to its good performance and inherent safety. The oxidizer is N_2O and a solid Paraffin-based fuel. The usage of liquefying fuels enables a simple single port fuel designs and a higher fuel utilization compared to low regression rate fuels like HTPB. The application of a self-pressurizing oxidizer permits a simple propulsion system with good performance, without external pressurization. The fuel of HyRES was designed for having high-performance in regression rate and mechanical properties[30] . Furthermore, a lot of effort was done to achieve a high combustion efficiency. It can be low for hybrid rocket engines, if the combustion chamber design is not optimized. The reason for this is that the fuel and oxidizer do not mix completely directly after injection, since the fuel mass flow is distributed over the length of the chamber. This forms typically a layered flow structure with an oxidizer-rich core and a fuel-rich outer periphery. Additional time and effort is needed to melt and evaporate the solid fuel and evaporate the liquid oxidizer. Different injectors, operating conditions and combustion chamber layouts were investigated to optimize this.

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Figure 1: HEROS rocket mounted on the launcher

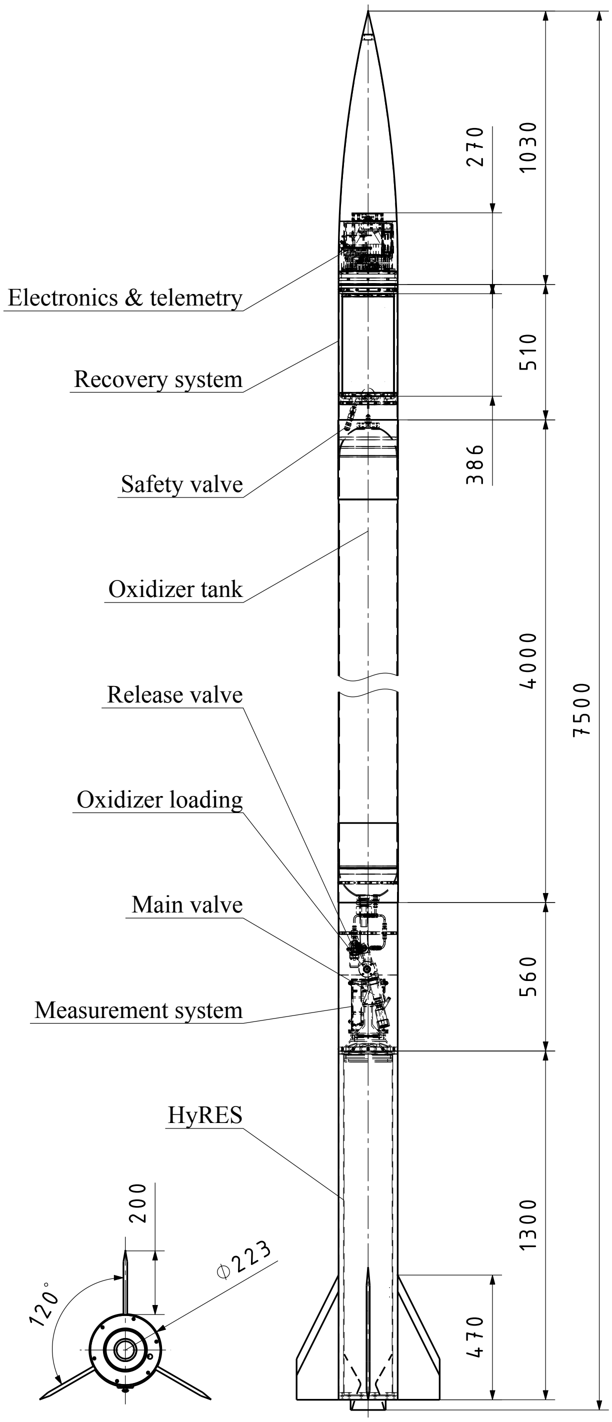

Figure 2: Overview of HEROS rocket and its subsystems

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4. Flight Campaign and Data Evaluation

4.1 HEROS 2 and 3 Flight

HEROS 2 was launched from the Mobile Rocket Launcher (MRL) in ESRANGE at 12:00 p.m. on October 31st, 2016. The lift-off is shown in Figure 3. It is nicely seen that the rocket plume is very clear without soot, which shows the high efficiency of the engine. However, an electronic interference right at T-0 of the countdown caused a failure of the on-board electronics and telemetry system. Without a telemetry signal it was not possible to get any information about the position during and after the flight of HEROS 2. The recovery system was most likely affected by the failure as well. A helicopter team searched at the nominal impact point, but due to the weather and sight conditions it was impossible to find the rocket. The video material and sound recordings were analyzed and all evidence suggests that the hybrid rocket engine HyRES worked nominally during the whole ascent of the rocket. In the following days the failure was investigated in detail and it was shown that an electronic interference with the main ignition impulse induced a voltage in the connecting line between the ground support computer and the rocket's on-board electronics. This voltage was high enough to generate a shut-off signal in the command line. Several successful improvements were made to prevent this malfunction for the third HEROS flight.

On November 8th, 2016 at 9:30 a.m. the hybrid sounding rocket HEROS 3 was launched from the ESRANGE Space Center to an apogee altitude of 32,300 m (106,000 ft)[6]. This set a new altitude record for European student and amateur rocketry and a world altitude record for hybrid rockets built by students [1]. An on-board camera image is shown in Figure 4 from the flight at apogee. Launch permission was given by the ESRANGE safety board after an extensive failure analysis of the HEROS 2 launch. The remaining launch window was open just until November 9th. The rocket configurations and the launch conditions are given in Table 2, respectively. The loaded oxidizer mass corresponds to a filling level of only about 70 % N_2O in the oxidizer tank. Moreover, the relatively flat launch angle of 80° further decreased the apogee altitude. This low angle was chosen by ESRANGE for increased safety during the launch, in order to let the rocket move away quickly from the launch site. Thereby, a significantly higher apogee is possible with HEROS 3, by loading more oxidizer and using a steeper launch angle. The trajectory of the flight is illustrated in Figure 5. GPS data is shown as well as the simulated trajectory from ASTOS.

Table 2: Launcher configuration and weather data for HEROS 2 and 3

	HEROS 2	HEROS 3
Launcher	MRL	MRL
Elevation	80 °	80 °
Azimuth	0 °	0 °
Launch Date	October 31st, 2016	November 8th, 2016
Launch Time [UTC]	12:00 p.m.	09:30 a.m.
Weather conditions	Cloudy, slightly foggy	Clear sky
Wind speeds (0-1 km)	2.1 m/s	6.3 m/s
Wind directions (0-1 km)	30 °	160 °
Ground temperature	0 °C	-18 °C

4.2 Flight Data Analysis of HEROS 3

All on-board measurements and sensors worked successfully and were analyzed after the recovery in detail. This includes data of the dedicated measurement system as well as the two redundant flight computers.

The combustion chamber pressure during the flight was very stable as it had been already demonstrated in the ground tests. Pressure and thrust build-up was very rapid and stable, ensuring a good initial acceleration on the launcher. The actual and the simulated flight trajectory is shown in Figure 5. GPS data was gathered during the rockets flight except the time frame between T+11 s and T+41 s. The COCOM Limit of the GPS modules was exceeded during this period. The data of all GPS modules show good consistency. The measured apogee heights are within 15 m of each other. The rocket could be located and was recovered within two hours due to the maintained GPS log and telemetry link during the entire flight. The GPS height compared to the calculated height of the IMU data, as well as the rockets velocity are shown in Figure 6. The flight computer recorded IMU data consisting of acceleration along three axes as well as the rotation rates around the same. Using this data, the rockets attitude was calculated with a self-made MATLAB tool. The calculated yaw and pitch angles are plotted in Figure 7, as well as the same angles according to the

[1] https://en.wikipedia.org/wiki/Amateur_rocketry [retrieved 20th May 2017]

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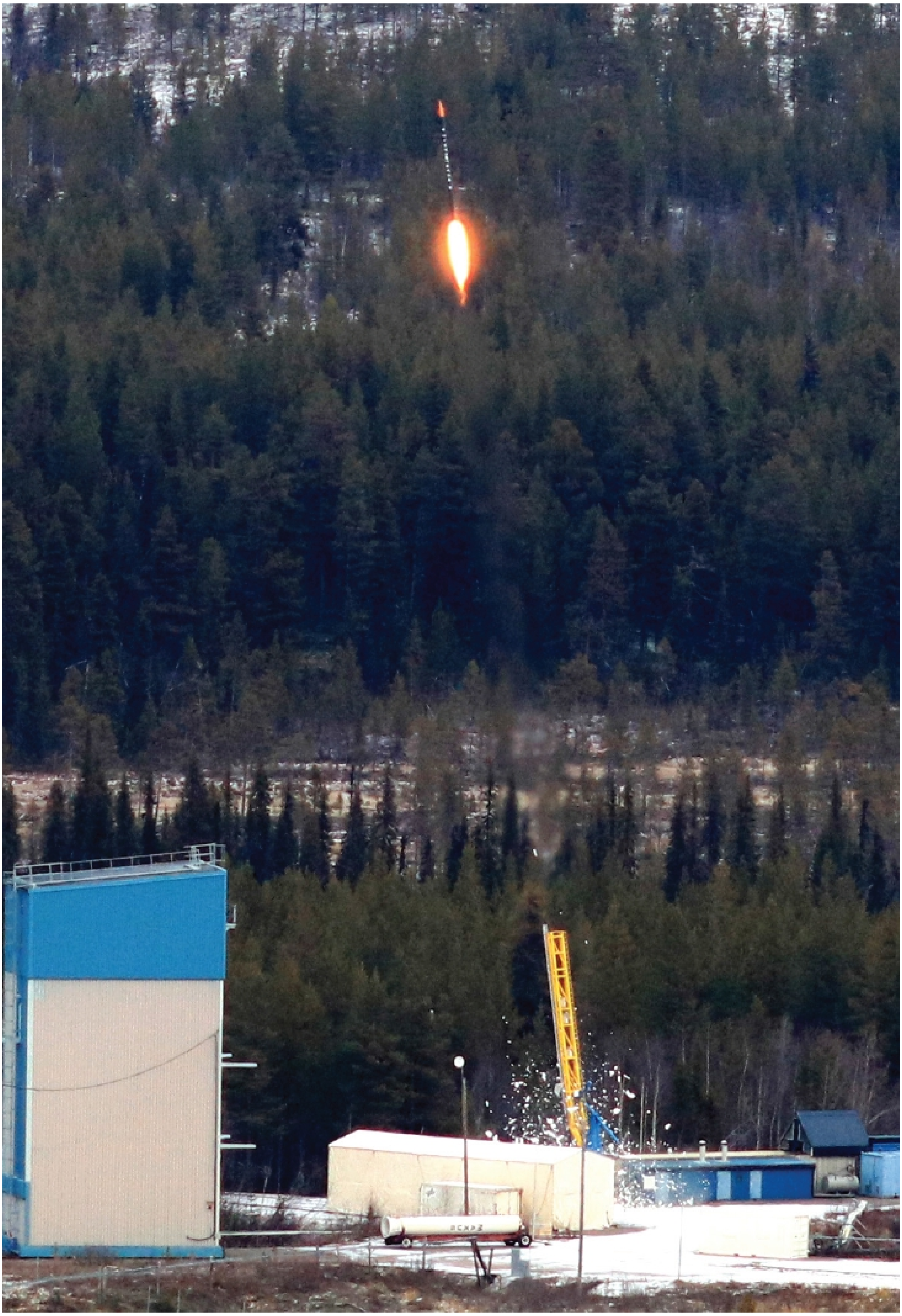

Figure 3: HEROS 2 at lift-off

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Figure 4: HEROS 3 on-board picture at 32,300 m apogee

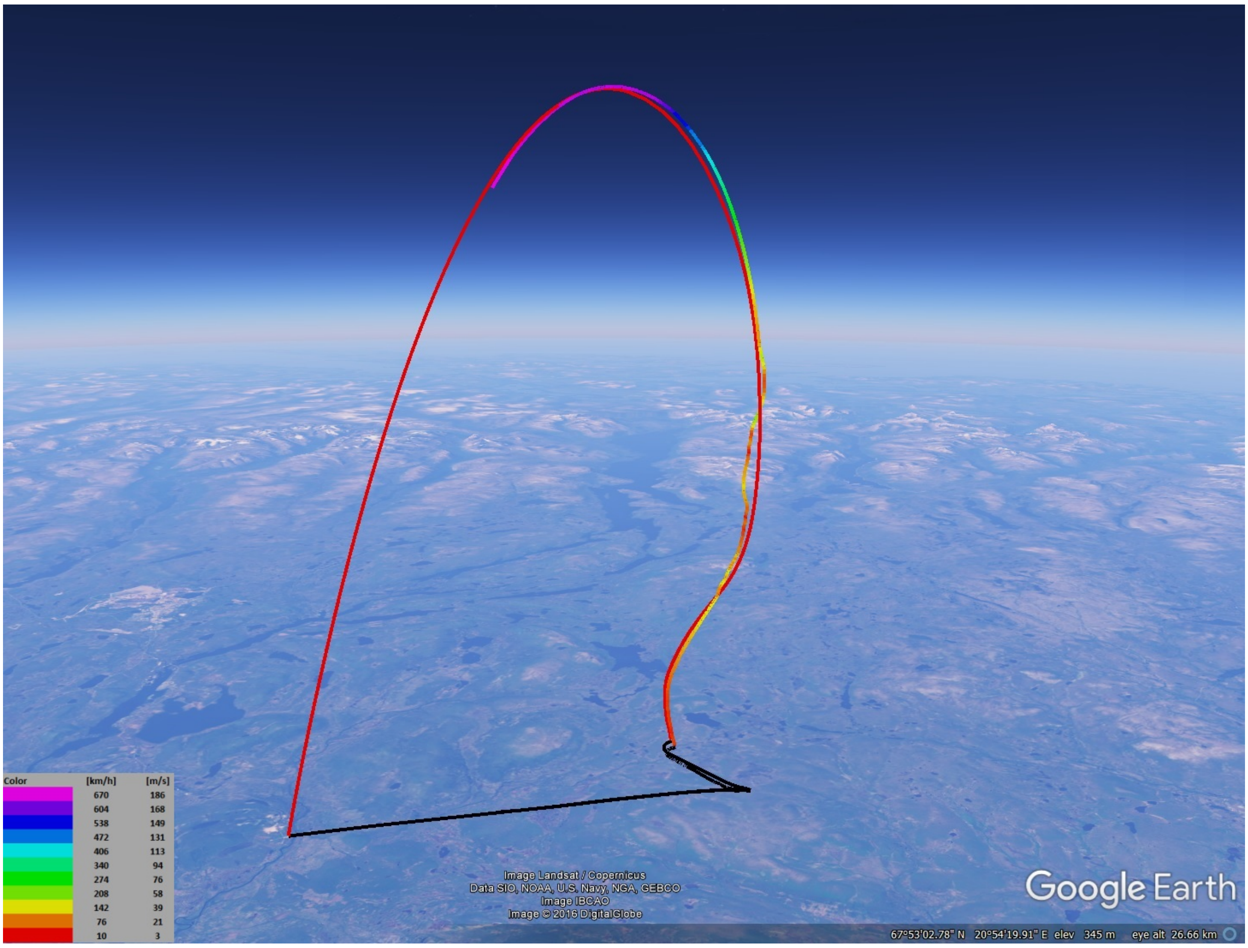

Figure 5: HEROS 3 flight: Trajectory simulation (red) and measured GPS flight data (colored). Data shown in Google Earth

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ASTOS simulations[14] . It is clearly seen, that the simulated and measured results fit almost perfectly. This confirms the applicability of the simulations and the used software tools. The maximum rotation rate around the longitudinal axis was at 0.5 Hz at liquid N_2O burnout. After that time, the roll rate was decreasing steadily until the apogee at around 90 s. A decrease in roll rate around this axis at 5.5 s is the time when supersonic velocity was reached.

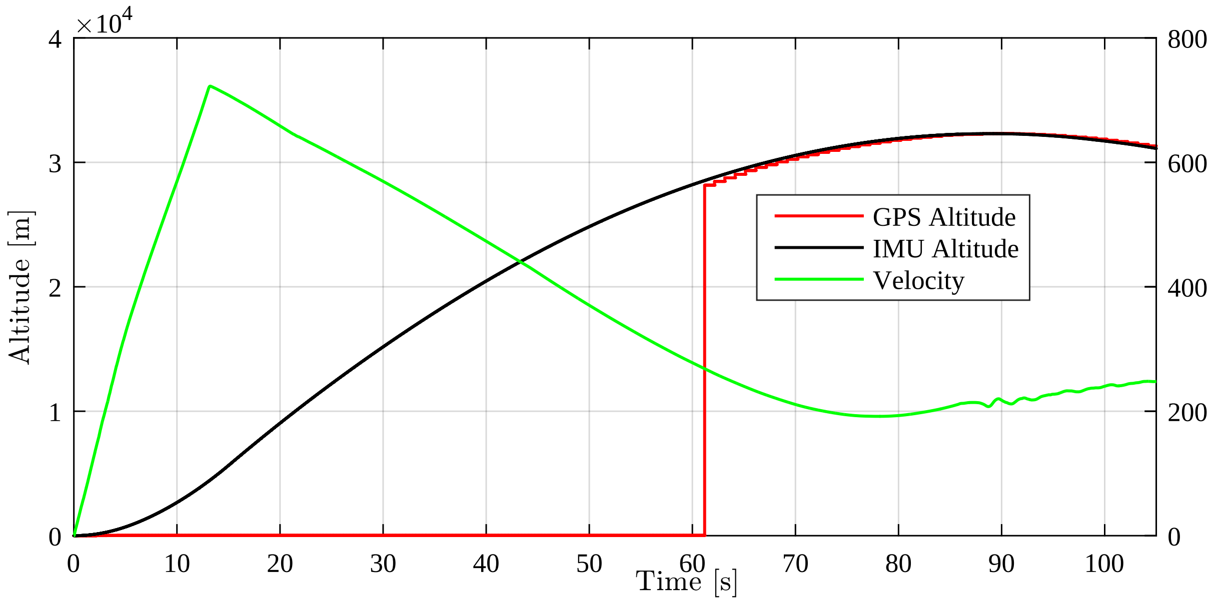

Figure 6: GPS altitude, calculated altitude and velocity of the rocket

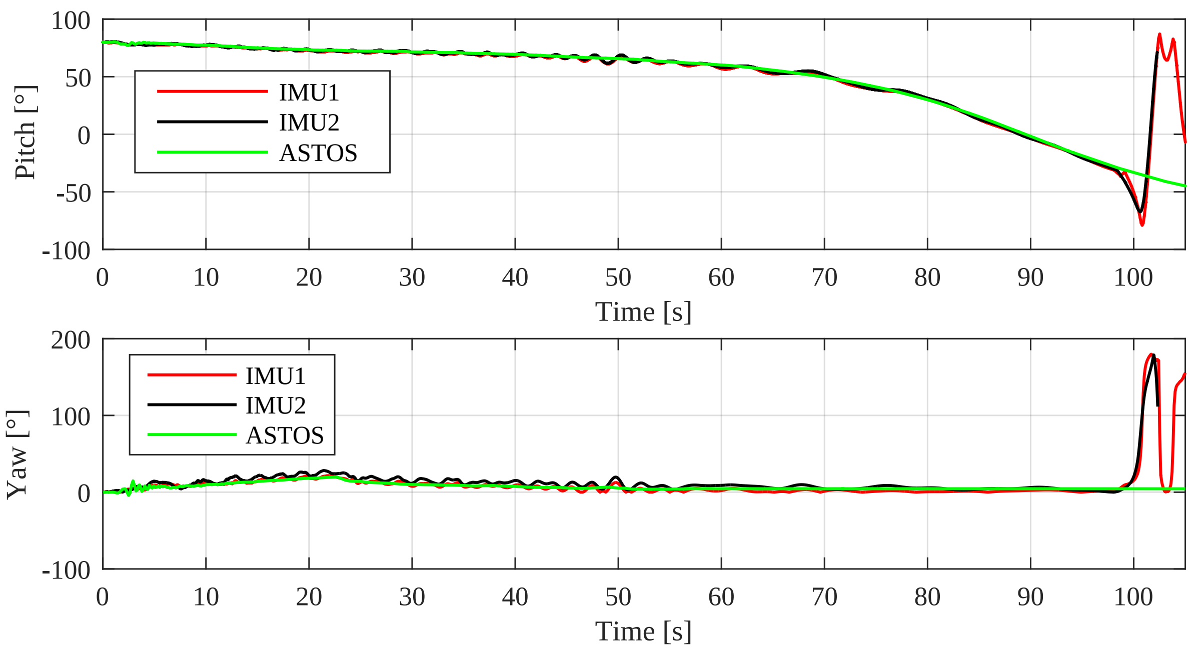

Figure 7: The rockets flight attitude, calculated from the on-board measurements, and the corresponding simulation results from ASTOS

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5. Conclusion

Three HEROS hybrid sounding rockets were developed, built and launched within just 4 years project time. The development involved the design of the complete rocket system, including the propulsion system, flight weight valve, rocket engine, tank, electronics, data acquisition, recovery system and rocket structure. The rocket itself, the subsystems, the qualification and the launch campaign were presented in detail herein. Despite drawbacks during the with the HEROS 1 and HEROS 2 launch, the project was continued and successfully completed; HEROS 3 was launched to 32,300 m (106,000 ft) and included a small student satellite experiment. Detailed flight data and engine performance data were published and analyzed. This is the first time that such detailed data is published for a hybrid sounding rocket flight. Also the use of a complete CFRP structure in such a hybrid rocket flight to this altitude is a novelty and a great technology demonstration. The rocket showed excellent aerodynamic stability as seen in the IMU data. The flight trajectory simulations with ASTOS showed very good agreements with the flight data from lift-off, to the apogee and to the landing point, including the effects of wind. In conclusion, this clearly shows the potential of hybrid rocket propulsion and hybrid sounding rockets. Moreover, the project enabled students to participate in the development and implementation of all the aforementioned systems, thereby providing them excellent hands-on experience in addition to their theoretical studies. Furthermore, a new world record for hybrid sounding rockets built by students was achieved.

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