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SKA RFS sounding rocket flight dynamics model validation based on flight data

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Abstract

Sounding rocket flight simulation is an important aspect of the design process and pre-flight preparations. In the former case, it allows for estimating the rocket's performance, its apogee, velocity and acceleration profiles, and in the latter, it is crucial to determine the launch safety by estimating the rocket's trajectory and impact point and velocity. In both cases, an accurate mathematical and physical model of the rocket and the environment is required in order to precisely predict the rocket's trajectory and behaviour in flight.

Every software tool used for the purpose of flight simulation requires verification and validation. Verification is a process of checking whether the prepared models were applied correctly, and validation is used to determine if the models themselves are correct. It is a process of determining whether and how accurately applied models represent reality. In order to do so, there is a need to establish metrics or thresholds for when to agree on the correctness of the model.

This paper will focus on the validation of the physical models implemented within the SKA Rocket Flight Simulation (SKA RFS) software, developed by the Rocketry Division of the Student's Space Association at the Warsaw University of Technology since 2018. The validation will be based on the flight data from the sounding rockets developed by the Association. Each rocket is equipped with inertial and satellite sensors, which provide, via integration methods, information about the rocket's state in flight in terms of position, orientation, velocity and acceleration. The collected information is transmitted as telemetry data during the flight and saved to the on-board computer's memory for further post-processing.

SKA RFS is a 6DOF flight simulation tool able to simulate multi-staged rockets, equipped with multiple engines, multiple parachutes, and aerodynamic control systems. The software is entirely written in the MATLAB environment. It includes the models of steady and unsteady aerodynamics, including the possibility of using lookup tables to store data obtained from CFD calculations or aerodynamic tunnel measurements in the form of aerodynamic coefficients. The software also includes the International Standard Atmosphere model with altitude- variable wind and accounting for the local atmospheric conditions near the launchpad. The models of inertial sensors, servomotors and the on-board computer are also included. The dynamic model of the rocket used within the software also handles the variable inertial properties of the rockets. Dynamic equations of motion are solved with the assumption of the oblate and rotating Earth using the WGS-84 Earth model.

The flight data, gathered using on-board inertial, barometric and GNSS sensors, will be post-processed and then used to validate the software in terms of the accuracy of predicted accelerations, velocities and altitude profiles, as well as the rocket's position and orientation.

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1. Introduction

The Students' Space Association (SSA) was established in 1996 at the Warsaw University of Technology (WUT), in the Faculty of Power and Aeronautical Engineering. Nowadays, SSA has over 200 members and is one of the most numerous students' associations at the Warsaw University of Technology. Currently, SSA has four divisions, each developing different space projects [1]. These include: Rocketry Division, Robotics Division, Balloon Division and PW-Sat3 project. The Rocketry Division, established in 2009 with the start of the first Amelia rocket project, has been designing and building record-breaking rockets to this day. The Division has had many achievements worth recognising. H1 - a supersonic rocket that was the fastest amateur rocket in Europe at the time, reaching the speed of Mach 2.7 [2]; FOK - an aerodynamically controlled rocket, utilised as a testbed for control and guidance algorithms [3,4]; TuCan - a CanSat launcher [5]; the Grot rocket is the current record holder for reaching 18,5 km - the highest altitude reached by an amateur rocket in Poland; Twardowsky rocket - the latest project of the Rocketry Division - first hybrid rocket at Warsaw University of Technology [6]. In addition to projects directly related to the construction of rockets, the Division has a huge analysis group that develops calculation software tools, which help to improve and optimise the designs. They also perform analyses in many essential fields, for instance in: aerodynamics, safety, flight simulation, mechanics of structures and propulsion. The analysis team currently develops three major tools: Rocket Flight Simulation (RFS) [7] program, Rocket Propulsion Analysis Tool (RPAT) [8] and Recovery System Tool. Each program, especially used for the flight simulation, should be as accurate and precise as possible. Therefore validation of the tool is necessary. In this paper, the validation of the physical model in the RFS is performed based on the flight data obtained from rocket launches performed in the past by the Association.

2. RFS model description

Rocket Flight Simulation [7] is a 3D six degrees of freedom (6DOF) flight simulation software developed in-house by the members of the Rocketry Division. It contains a full nonlinear model of variable mass rocket dynamics and is capable of handling multi-stage rockets with multiple parachutes, multiple engines and aerodynamic control, including the simulation of on-board computer (OBC). The core of the model is a set of 6DOF equations of motion of a variable mass object with quaternion-based attitude kinematics. The equations are derived with respect to a non-inertial Earth Centred Earth Fixed (ECEF) reference frame. The loads acting on the rocket include gravity, aerodynamics, induced by the fuselage itself, the aerodynamic control surfaces, parachutes and propulsion in terms of rocket motors. The rocket's inertia properties, mass, the centre of mass and inertia tensor, are defined as the sum of inertia properties of the rocket's body and its motors. When the rocket motors burn, they change their inertia properties and thus alter the inertia of the entire rocket. The aerodynamic model calculates the forces, in terms of drag, side force and lift. Rolling, pitching and yawing moments acting on the rocket are modelled as functions of incidence angles and angular velocities [9]. The loads are modelled using a set of coefficients tabularized as functions of Mach number and interpolated during simulation execution. For aerodynamic control surfaces, an additional set of coefficients is introduced describing the variations of aerodynamic coefficients as functions of canards' deflection angles. The parachute descent is modelled by accounting for the drag coefficient of the chute. The atmosphere is modelled using the International Standard Atmosphere, accounting for the local conditions at the launch site. It defines pressure, density, temperature and speed of sound as functions of altitude. Additionally, a vertical profile of horizontal wind, in terms of velocity and heading as functions of altitude can be provided. The simulation allows for specifying various control algorithms that can be simulated as a part of the OBC that allow for flight stabilisation and trajectory control. The launch is simulated using the model of the rail launcher.

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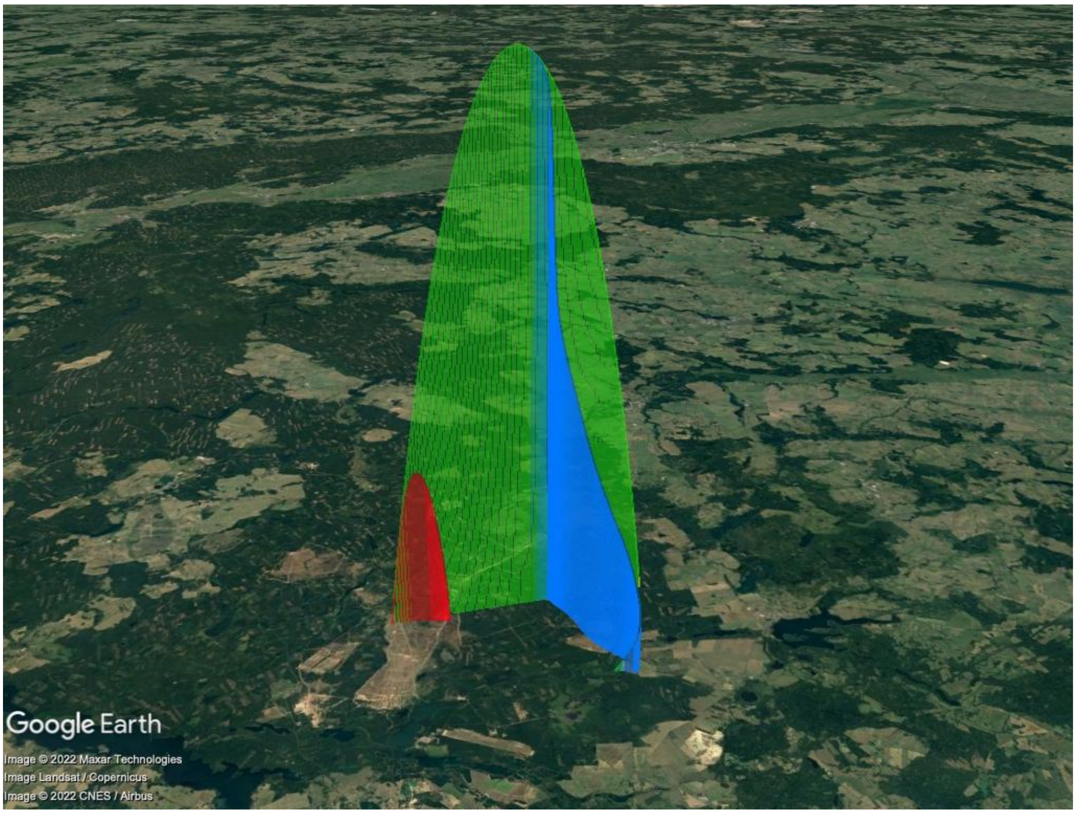

Figure 1: Grot rocket trajectory visualised in Google Earth Pro

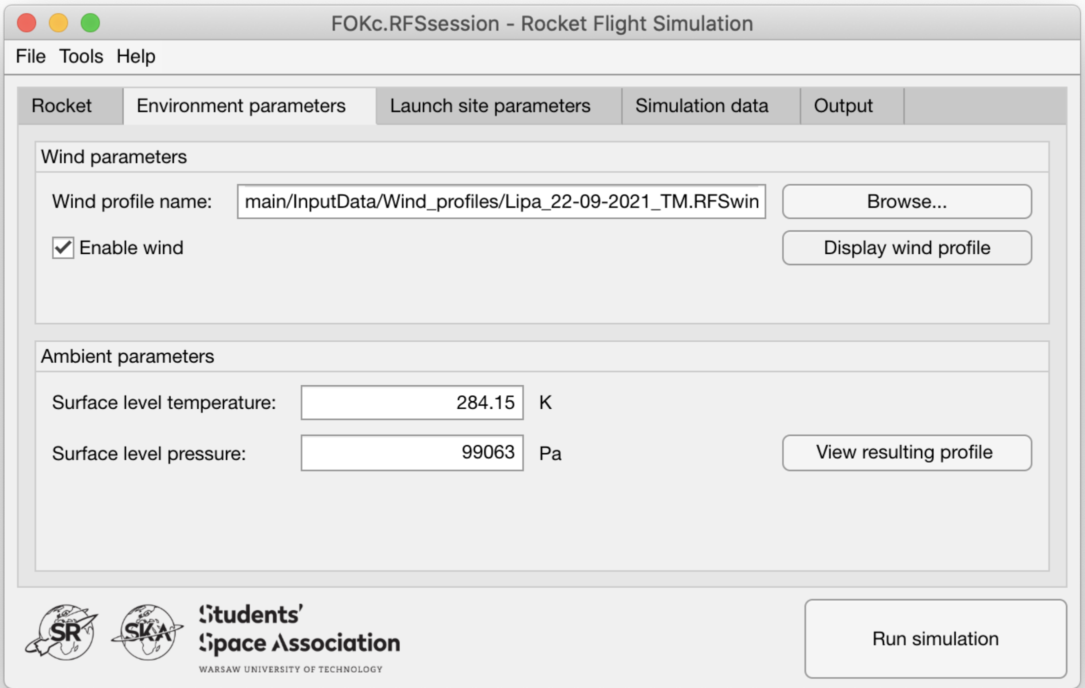

Figure 2: GUI of the RFS software

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3. Model validation description

The model used inside the RFS will be validated by comparing results predicted by the simulation and real flight data. Four flights have been selected to perform the validation namely A2e, TuCAN(b), and two iterations of the FOK rocket: FOK-1B and FOK-1C. The choice of those flights was based on the fact that they were performed with an appropriate on-board computer and that the computer was recovered after the flight intact. This second requirement is very important as only the data stored in on-board memory have a high enough sampling frequency to be used during validation. The sampling of data received via telemetry is not sufficient as some of the data frames are lost, thus incorporating large gaps to the measured values, making the comparison less valuable. Only flight data up to the apogee were analysed, since the parachute opening happening afterwards heavily affects the dynamics of the rocket.
The comparison will be performed using quantities that can be both measured by the onboard electronics and calculated by the simulation model. During all four flights, the rockets carried an Altus Metrum TeleMega onboard computer [10]. TeleMega is equipped with the following sensors: barometric pressure sensor, 1-axis 200-g accelerometer, 3-axis 16-g accelerometer, 3-axis 2000 deg/sec gyro, 3-axis magnetic sensor and an on-board, integrated GPS receiver. FOK-1C also carried a high-performance GNSS-aided inertial navigation system VectorNav VN-200 [11] equipped with a barometric pressure sensor, 3-axis 16-g accelerometer, 3-axis 2000 deg/sec gyro, 3-axis magnetic sensor and GNSS receiver including high-quality calibration and inertial navigation algorithms. It was decided that for all flights the barometric pressure, acceleration, angular rates and flight trajectory will be compared with simulated data. Additionally, for the FOK-1C flight velocity and attitude will be compared using the output of the inertial navigation system.

3.1 A2

The Amelia 2 (A2) rocket was the second rocket developed by the Students' Space Association. It was a two-staged rocket based on the first rocket - Amelia 1. A2 was approximately 2.3m long and weighed around 7kg. The main materials used in the construction were carbon fibre and glass fibre composites and aluminium [2,12]. Both stages were equipped with identical HTPB-based solid rocket motors, with a specific impulse of 2200m/s and a thrust of 700N. It was designed to reach an apogee of 3km, with a maximum velocity of around 300m/s. Each stage of the rocket had a parachute recovery system allowing for a safe descent. The rocket was equipped with a Telemega on-board computer, which was recording parameters during the flight and was also responsible for the separation and parachute deployment. A2 version "e" was launched on 22.10.2016 on the military range near Toruń. Figures 4-8 represent a comparison between the simulation and real flight data.

Figure 3: A2 rocket on the launch rail during the rocket launch test

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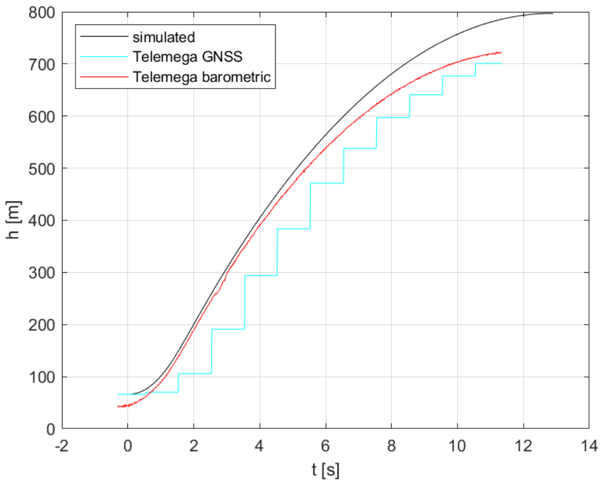

Figure 4: Comparison of altitude for A2e flight

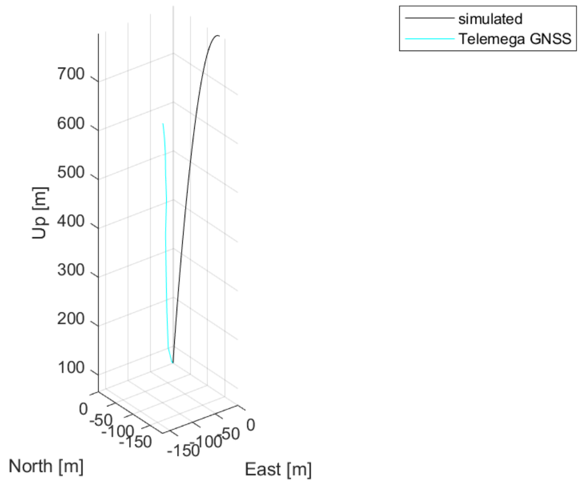

Figure 5: Comparison of 3D trajectory for A2e flight

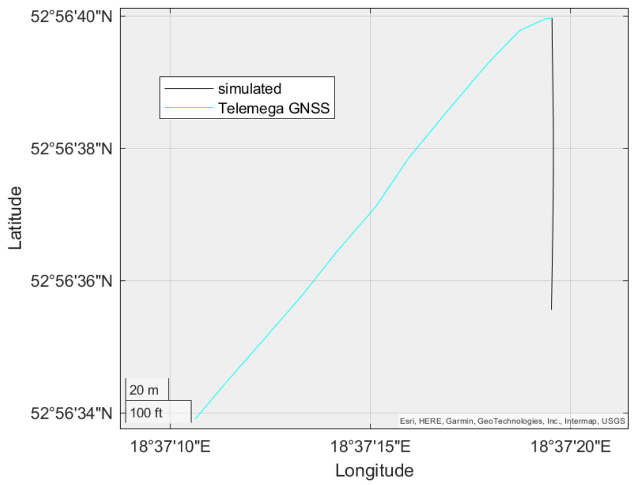

Figure 6: Comparison of geographical coordinates for A2e flight

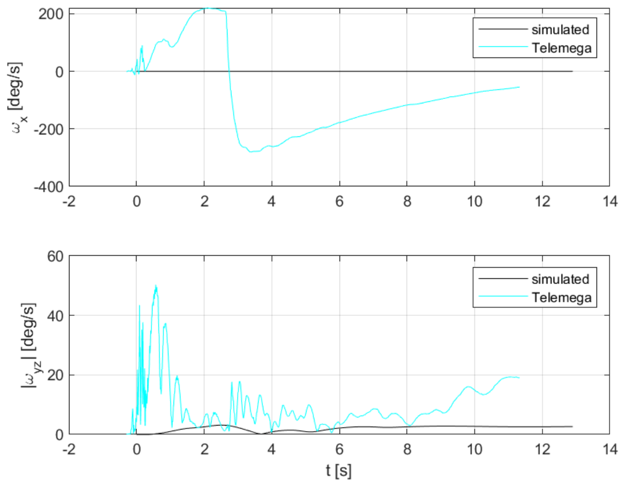

Figure 7: Comparison of angular rates for A2e flight

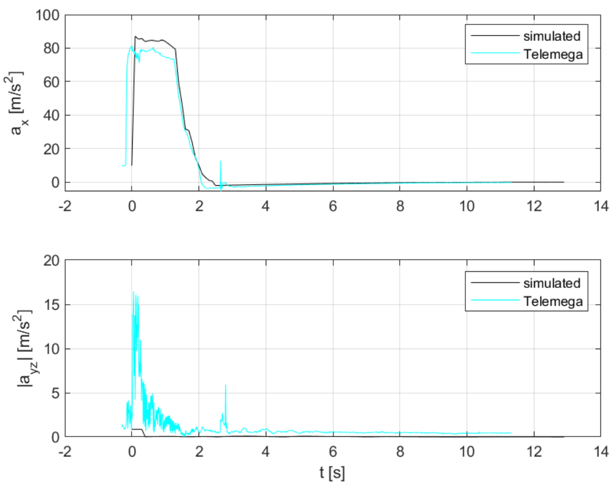

Figure 8: Comparison of accelerations for A2e flight

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3.2 TuCAN

TuCAN was the fourth rocket developed in the Association. Its objective was to release eight experiments (CanSats) at an apogee of around 4km [5]. A CanSat is a small experiment that can fit into a soft drink can. The rocket consists of one solid motor engine, on-board computer, recovery system and CanSat deployment module. TuCAN was approximately 2m long and its total take-off weight was around 28kg. The idea of developing a CanSat launcher was the original motivation behind establishing the Association's Rocketry Division. TuCAN was launched two times in total. First in 2016, but due to a recovery system failure, the flight data computer was lost. During the second launch, on 2.12.2017, the entire mission plan was achieved. Figures 10-14 represent a comparison between the simulation and real flight data.

Figure 9: The TuCAN rocket

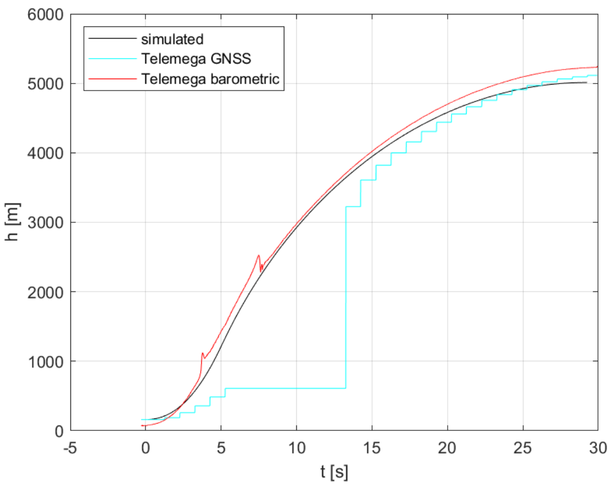

Figure 10: Comparison of altitude for TuCAN flight

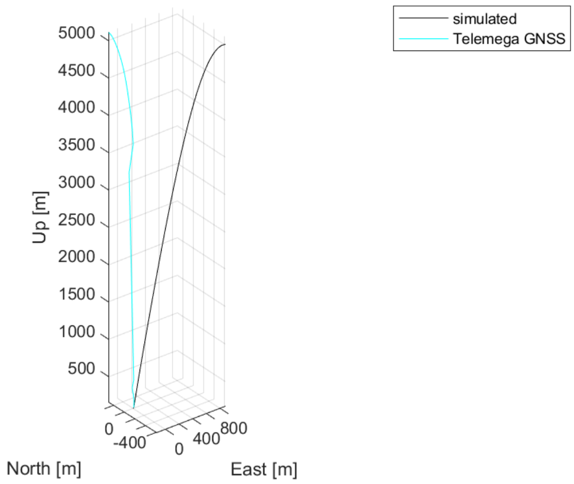

Figure 11: Comparison of 3D trajectory for TuCAN flight

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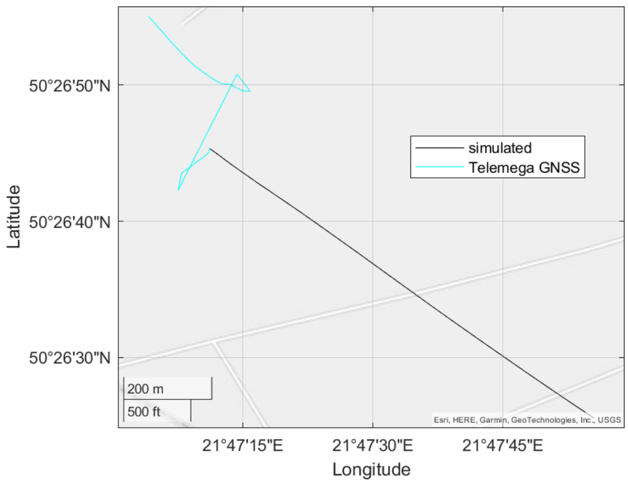

Figure 12: Comparison of geographical coordinates for TuCAN flight

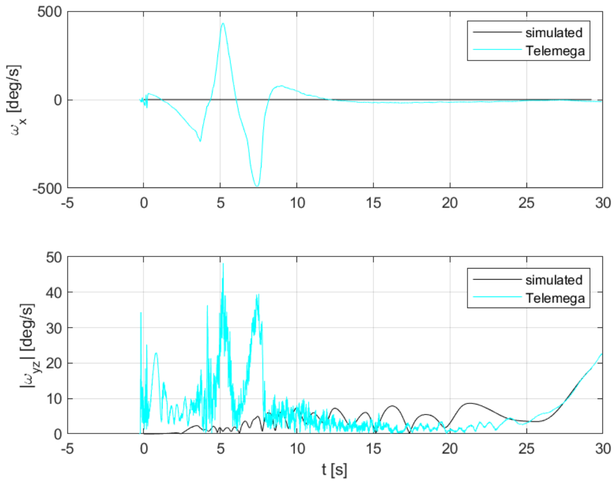

Figure 13: Comparison of angular rates for TuCAN flight

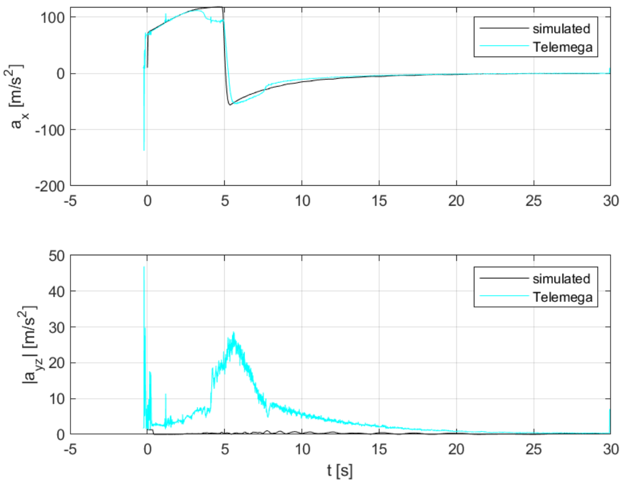

Figure 14: Comparison of acceleration for TuCAN flight

3.3 FOK

FOK is an aerodynamically controlled guided missile equipped with four forward control surfaces [3,4]. The project began in 2017 and since then the rocket had three successful launches, in 2018, 2019 and 2021. FOK is 75 mm in diameter and 1.4 metres long and is powered by a solid rocket motor which provides about 590N of mean thrust during 2 seconds of working time. Its aerodynamic coefficients were determined using data from the wind tunnel tests performed at the Faculty of Power and Aeronautical Engineering at the Warsaw University of Technology. The rocket is equipped with two on-board computers, Ganymede and TeleMega, the first being the primary one responsible for generating control commands and saving data from the VectorNav VN-200 navigation unit, and the second being the redundancy. The aim of the project was to create a simple and fully reusable test platform for testing various control algorithms. Figures 16-20 represent the comparison between the simulation and real flight data from the FOK-1B rocket launched on 29.09.2019 and Figures 21-26 represent a comparison of the FOK-1C flight (22.05.2021).

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Figure 15: FOK rocket on the launch pad, version 1B (right) and 1C (left)

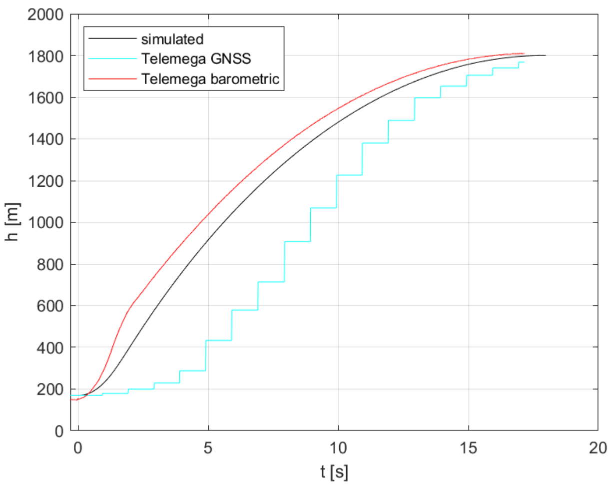

Figure 16: Comparison of altitude for FOK-1B flight

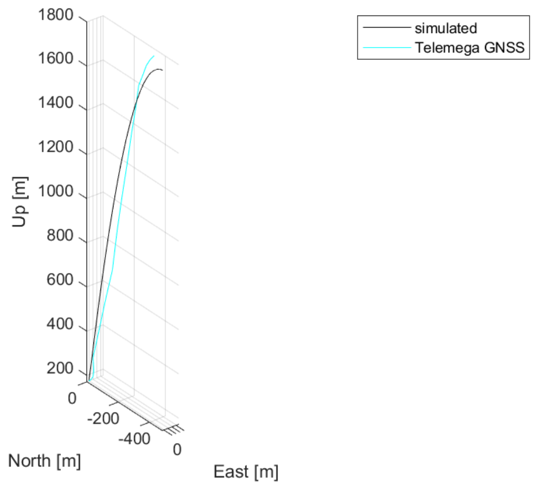

Figure 17: Comparison of 3D trajectory for FOK-1B flight

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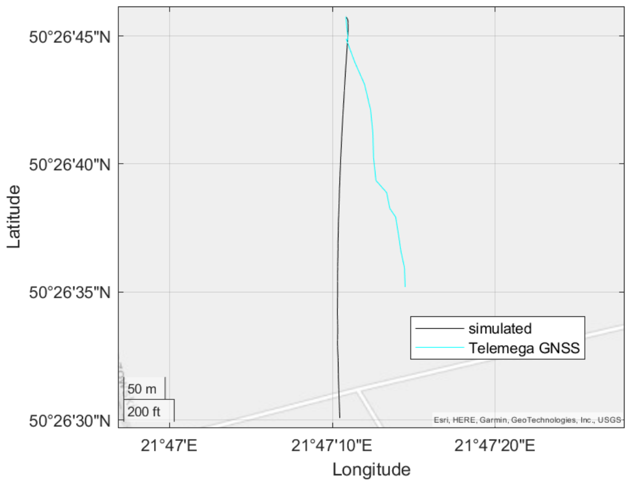

Figure 18: Comparison of geographical coordinates for FOK-1B flight

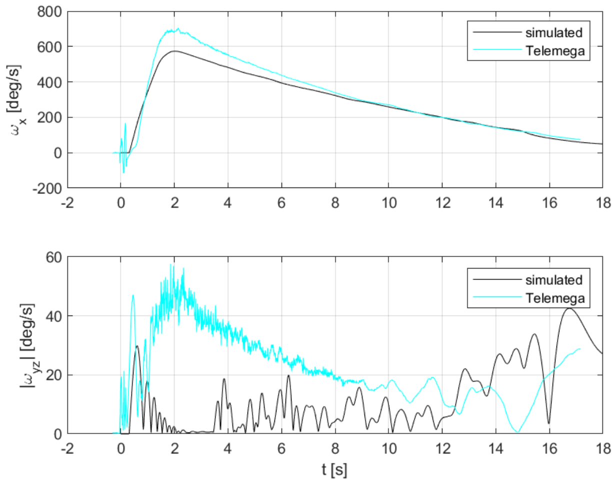

Figure 19: Comparison of angular rates for FOK-1B flight

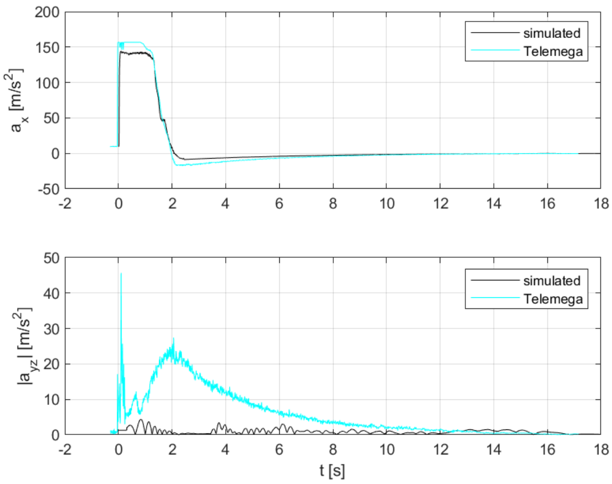

Figure 20: Comparison of acceleration for FOK-1B flight

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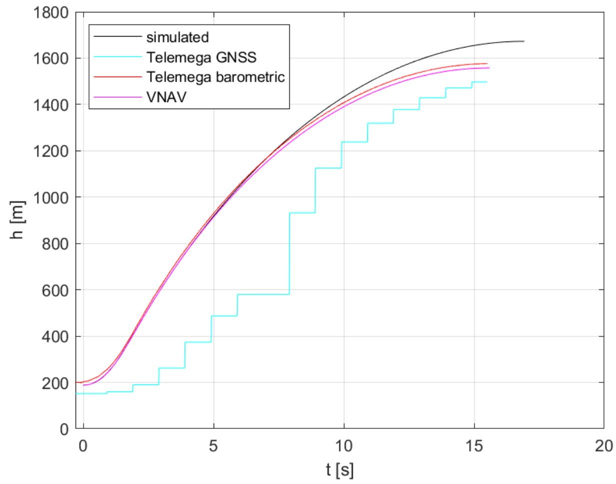

Figure 21: Comparison of altitude for FOK-1C flight

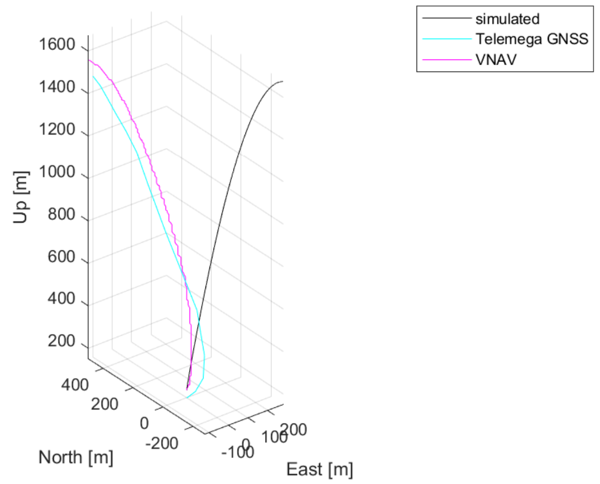

Figure 22: Comparison of 3D trajectory for FOK-1C flight

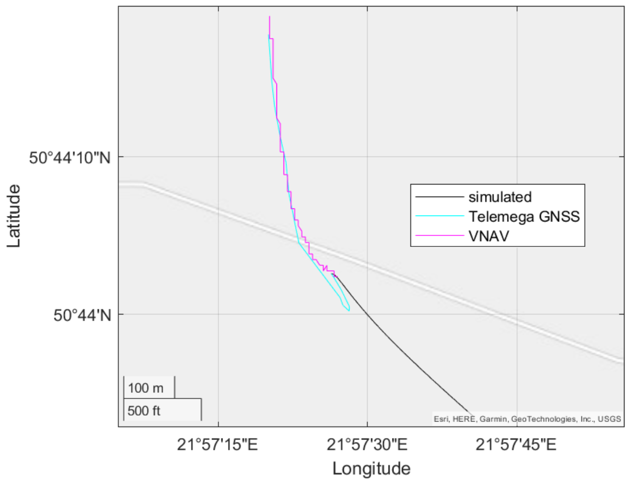

Figure 23: Comparison of geographical coordinates for FOK-1C flight

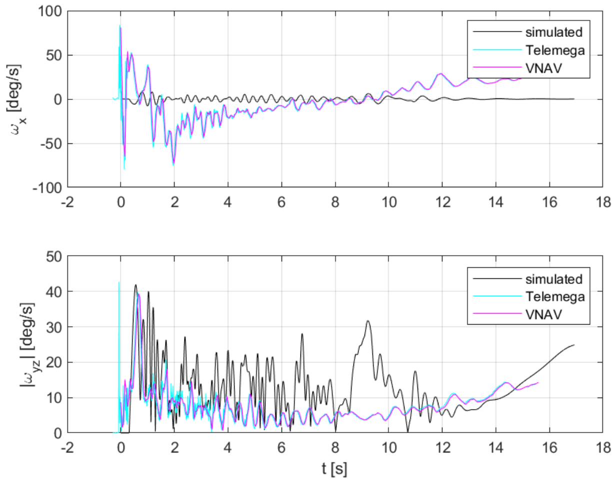

Figure 24: Comparison of angular rates for FOK-1C flight

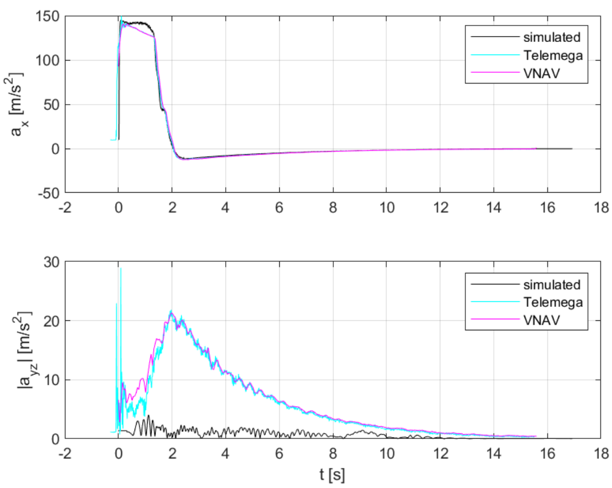

Figure 25: Comparison of acceleration for FOK-1C flight

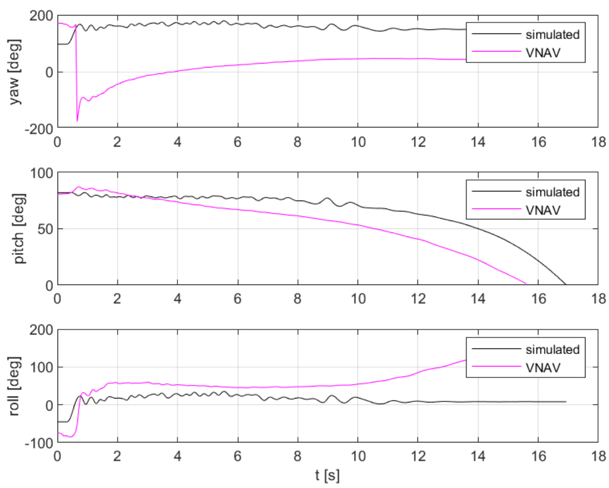

Figure 26: Comparison of attitude angles for FOK-1C flight

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4. Discussion

The discussion of the results will begin with the comparison of 3D trajectories (Figures 5, 11, 17 and 22). One can immediately notice that the trajectories (simulated and observed in flight), although resembling the same shape, do not follow the same direction. This is mostly due to the fact that during launch, small rockets are prone to turning into the incoming wind, whose instantaneous velocity is hard to establish.
Figures 4, 10, 16 and 21 show that the height of the rockets during the flight tests closely resembled the height determined in the simulation. The maximal error between the simulated and measured apogee height was 10% considering barometric height and 12% considering GNSS height. The differences might be due to two reasons - the inaccuracies of the rockets' aerodynamic and inertial parameters, as well as some inaccuracies in the rockets' motor thrust curves used in the simulations. The differences between the assumed and real thrust curves are visible in the acceleration plots (Figures 8, 14, 20, 25), however, they cannot be entirely interpreted as modelling error. Every solid propellant grain has slightly different characteristics, the effects of which cannot be accurately measured without experimental tests, which use up the grain.
Further analysis of the acceleration plots shows that the transverse components represent a significant discrepancy with the simulated data - their fluctuations have the same order of magnitude as the ones caused in the simulation by the wind, but there exists an interesting phenomenon. During the work time of the motor, the transverse acceleration increases almost linearly, and then after the grain burn-out decreases. This suggests that there exists a phenomenon not accounted for within the simulation model. In case of FOK flights, these could be caused by slight canard deflection, resulting from mounting errors during integration of the rocket.
The correlation between angular rates registered in flight and predicted by the simulation (Figures 7, 13, 19 and 24) varies significantly. During the flight of the A2 rocket, a noticeable rolling rate is observed, which changes direction during the flight. It was a result of a sudden change in a sign of roll coefficient, caused by staging of the rocket, leading to a rapid change in angular rate.
The fast change in direction of motion immediately after the rocket leaves the launch rail, most probably caused by the wind or slight canard deflection, can also be observed in Figure 26, as the yaw angle changes rapidly in the first second of the flight.This effect is different for each flight and might be caused by the method of modelling the launch rail in the RFS. During the initial phase, the flight can be divided into two major parts. First when the rocket is on the launch rail (and therefore is constrained to move only in the forward direction), second when the rocket is no longer on the launch rail allowing it to freely move in all 6DOF. In order to improve this important part of the rocket flight, analysis team members are currently developing a model of tip-off effect, which can significantly influence the flight when the rocket leaves the launch rail. Additionally, this change in direction is most likely not caused by non-axial thrust of the rocket motor as there is no transverse acceleration component correlated with the thrust generated by the motor (Figure 8, 14, 20 and 25).

5. Conclusions

This paper presents the validation of a sounding rocket simulation model by comparing simulation results with real flight data. Except for a single phenomenon (flight direction changes immediately after the rocket leaves the launch rail), all other discrepancies between the simulation and real flight data can be explained by inaccuracies in the rockets' input data and phenomena of random nature (e.g. wind gusts). The main rocket parameters, such as the achieved altitude, are predicted correctly. To investigate the encountered rockets' behaviour, further research of the observed launch rail escape is required. A more elaborate model of rocket motion on the launch rail is already being developed with the goal to introduce individual reactions between rocket sliders and launch rail - this will allow simulating the launch phase when the rocket is partially constrained by one slider and is most susceptible to deviating from its original attitude. The quality of the rocket input parameters have had a significant impact on the simulation outcomes. Therefore, the inaccuracies should be minimised. For instance, in the Association there are special test campaigns, whose goal is determining aerodynamic coefficients based on the aerodynamic tunnel data, carefully measuring inertia parameters of the rockets and static fire tests providing necessary thrust curves.

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