Copenhagen Suborbitals

Flight report

HEAT-1X / Tycho Brahe

June 3rd 2011

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TYCHO BRAHE

1 Introduction

1.1 Launch!

On June 3rd 2011 Copenhagen Suborbitals launched its HEAT-1X rocket carrying the Tycho Brahe spacecraft. The launch took place from a military shooting area, ESD 139, approximately 30 km east of Bornholm. The launch was originally planned for the summer of 2010 but a faulty valve kept the vehicle on the ground, or rather, on the water. Since there is no land location in Denmark with a safety range in excess of 20 km the launch has to be done at sea. Thus a 12 ton heavy, 12 by 14 meter Mobile Launch Platform (MLP) capable of carrying the rocket and all necessary components including personnel was built. The launch platform, named Sputnik, the HEAT-1X rocket and the Tycho Brahe spacecraft are all seen in the image in Fig. 1.1.

The launch operation started at 7 AM on the morning of June 3rd. Sputnik and her three man crew (Kristian Elof Sørensen, Claus Nørregaard and Claus Mejling) were the first to leave Neksø harbour. They were followed by Leopold Rosenfeldt, a Search And Rescue ship who where to provide assistance in case of emergency. Leopold Rosenfeldt also carried part of the CS crew to the launch site. At 10 AM MHV 903 Hjortø, an inspection ship from the Danish Naval Home Guard, left Neksø bound for ESD 139. The launch operation was directed from Hjortø who carried CS Mission Control, a television crew from Danish TV2 and a crew from Weibel Doppler Radars along with a doppler radar setup. CS Mission control consisted of Flight Director Kristian von Bengtson, Fligt Dynamics Officer Steen Andersen, COM Thomas Scherrer and Flemming Nyboe. Additionally two RIBs, Recovery Alpha and Bravo, served as personnel transfer vehicles, photo platforms and recovery boats. Thus, the operation consisted of five vessels and during the final part of the fueling operation, the launch itself and the recovery operation a helicopter from Danish TV2 also participated.

Launch preparations started shortly after noon and where carried out by Pad Leader Niels Foldager and Peter Madsen assisted by the Sputnik crew. The entire operation was supervised by Mission Control on Hjortø. During launch preparations Leopold Rosenfeldt and Hjortø spend a substantial

Figure 1.1: Sputnik carrying HEAT-1X / Tycho Brahe towards the shooting area early in the morning on June 3rd. The two large structures on either side of the deck are two 630 liter LOX tanks.

amount of time rejected traffic into the military shooting area which had been shut down for traffic. The air space was also shut down and incoming flights were diverted by air traffic controllers.

At 3.32 pm HEAT-1X took off from the launch platform in a massive plume of smoke and water vapor. As the vehicle cleared the tower it pitched over to fly at an angle of about 30 degrees to horizontal. As a consequence of the undesirable flight path the motor was shut down after 15 seconds at an altitude of 1400 meters. The low flight angle inevitably lead to a high horizontal velocity at the moment of parachute deployment. This lead to parachute malfunction and the booster impacted the water at a very high speed causing it to disintegrate and sink. The spacecraft landed with a single partially torn parachute deployed causing significant damage. Despite being filled with water the spacecraft kept afloat and was recovered by Recovery Alpha.

For more information on the launch operation, videos and still images please visit www.copenhagensuborbitals.com.

1.2 Vehicle specifications

1.2.1 General

The launch vehicle and spacecraft are seen in Fig. 1.2. The total height is 9.38 meters excluding the arrow spike and the projected lift off weight is 1627 kg including propellants. The vehicle is divided into several sections as illustrated in Fig. 1.3. Component masses and their Center of Gravity (CG) relative to the aft booster flanger are listed in table 1.1.

1.2.2 Propulsion

The booster is a hybrid motor running on a solid polyurethane (PUR) grain in a 12+1 wagon wheel configuration and liquid oxygen (LOX). A drawing of the fuel grain is given in Fig. 1.4. The LOX

Figure 1.2: HEAT-1X and Tycho Brahe assembled in July 2010.

Table 1.1: Table of component positions and masses used to calculate total CG. Positions are relative to the aft flange on the booster. Note that this table does not include any components installed between LC 2010 and LC 2011. The largest component thus not included is the LOX chiller.

Component	Start Position [cm]	Start Mass [kg]	MECO Position [cm]	MECO Mass [kg]
Booster	206.3	452.1	206.3	452.1
Fuel	125.5	305.6	128.1	94.6
LOX	340.5	534.5	0	0
BRM	539.4	35	539.4	35
Spacecraft and SRM	733.5	300	733.5	300
Total	339.6	1627.2	390.5	881.7

tank has a volume of 700 liter but is only filled 2/3 with LOX. The tank is pressurized to 25 bar with helium and thus the ullage of pressurized helium feeds LOX through the injector and into the combustion chamber. At ignition the propellant flow rate is in the order of 40-45 kg/s providing an initial thrust of about 65 kN.

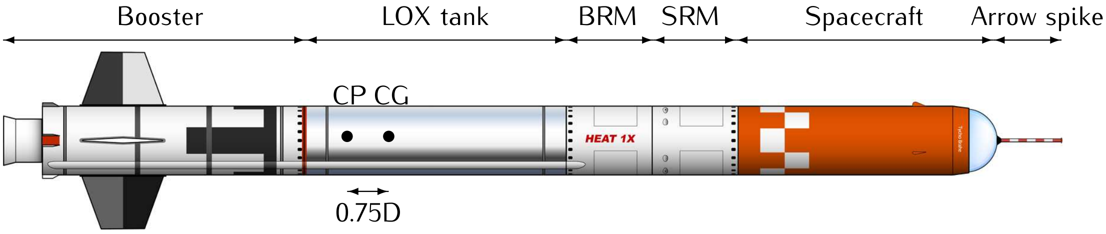


Figure 1.3: Drawing of HEAT-1X / Tycho Brahe. BRM - Booster Recovery Module. SRM - Spacecraft Recovery Module. Center of Gravity (CG) and Center of Pressure (CP) are indicated on the figure.

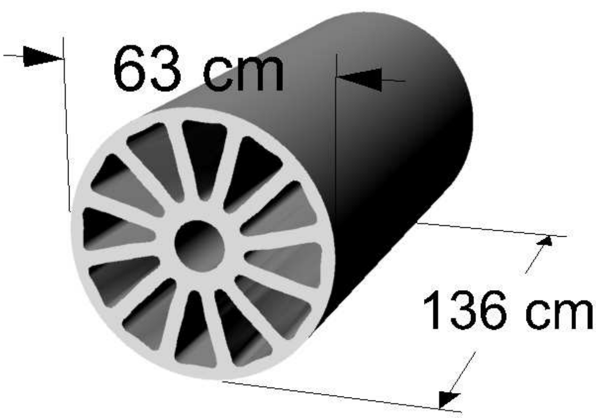


Figure 1.4: 12+1 wagon wheel configuration fuel grain used in HEAT-1X.

1.2.3 Electronics

The vehicle is fitted with custom made electronic solutions to serve a number of purposes. First of all it has a radio controlled launch system. This system is activated upon reception of a certain 64 bit code. When activated the internal computer takes control of the launch sequence and initiates a 60 second countdown. At T-4 the pyrotechnic charges in the combustion chamber are fired and at T0 the LOX valve is opened and the vehicle lifts off. When the launch sequence is initiated at T-60 a warning light is lit and a horn is sounded on the launch platform to warn any personnel on board. Needles to say, no personnel should be on the launch platform at this stage but in the case of untimely launch sequence activation the MLP is fitted with an abort button to abort the launch.

By the same radio control system booster and spacecraft separation, drogue deployment and parachute deployment are initiated from Mission Control (MC). In the event of loss of radio communications with the vehicle a timeout is programmed into the onboard computer such that the parachutes are released before nominal impact. The system is equipped with a safety feature such that MC can close the LOX valve and shutdown the motor by radio. This will be done if the trajectory is found to be in danger of bringing the vehicle outside the military shooting terrain.

The trajectory or flight path is monitored by the onboard computer. This unit basically consists of three accelerometers, three gyroscopes and a microprocessor. Based on measurements from the sensors the microprocessor computes the velocity and position at a rate of about 200 Hz. All data is stored on a memory card, position data are however relayed by radio to MC where they are used by the Flight Dynamics computer. This receives position data at a rate of about 2 Hz and uses this data to show the Flight Dynamics Officer (FIDO) important information such as speed, altitude, direction and other parameters. The information is also used to predict a landing or impact location. If the landing or impact location is seen to move towards the edge of the military shooting terrain during flight, FIDO will inform the Flight Director who will then abort the flight by shutting down the motor and initiate booster/spacecraft separation and parachute deployment.

2 Motor performance

The motor was test fired in May 2010 with a 16 second burn. The combustion chamber pressure curve is shown in Fig. 2.1(a). A large amplitude, low frequency oscillation is apparent, a pressure spectrum plot is seen in Fig. 2.2(a). The oscillation frequency is about 9.5 Hz initially and drops of to 7.5 Hz at MECO. During flight the combustion chamber pressure was also measured and this is plotted in Fig. 2.1(b), a corresponding pressure spectrum plot is shown in Fig. 2.2(b). The pressure measured during flight is almost identical to that measured during the static test. However, during the first 1-2 seconds the oscillation amplitude is significantly smaller during flight and also the frequency is about 1 Hz lower than for the static test. The partial stability for the first 1-2 seconds can be due to at least two differences. First of all the initial LOX tank pressure was higher during flight than for the static test. This is illustrated in Fig. 2.3(a) where low pass filtered versions of the combustion chamber pressures and LOX tank pressures are plotted. For the static test the initial LOX pressure was 21 bar and for flight it was increased to 25 bar. This leads to a slightly higher injector pressure drop for the flight version as illustrated in Fig. 2.3(b). Another interesting parameter is the relative injector pressure drop (relative to combustion chamber pressure), this is plotted in Fig. 2.4. For the first second the relative pressure drop is 50% for the flight motor whereas it is only 40% for the test motor. Another factor that might account for the initial "stability" of the flight motor is the fact that a pilot light like ignition device was used. A potassium nitrate and sorbitol slab was implemented as part of the pyrotechnic ignition system on the flight motor. Thus, for the first few seconds the injected LOX is preheated by the burning slab. A flame holding instability will benefit from such heating (G.P. Sutton, 7th edition page 601).

During static test the total impulse was measured to be 507000 Ns with an estimated propellant consumption of 344 kg. This gives a specific impulse of 149 s for this motor. It is assumed that the specific impulse of the flight motor is similar to that of the test motor.

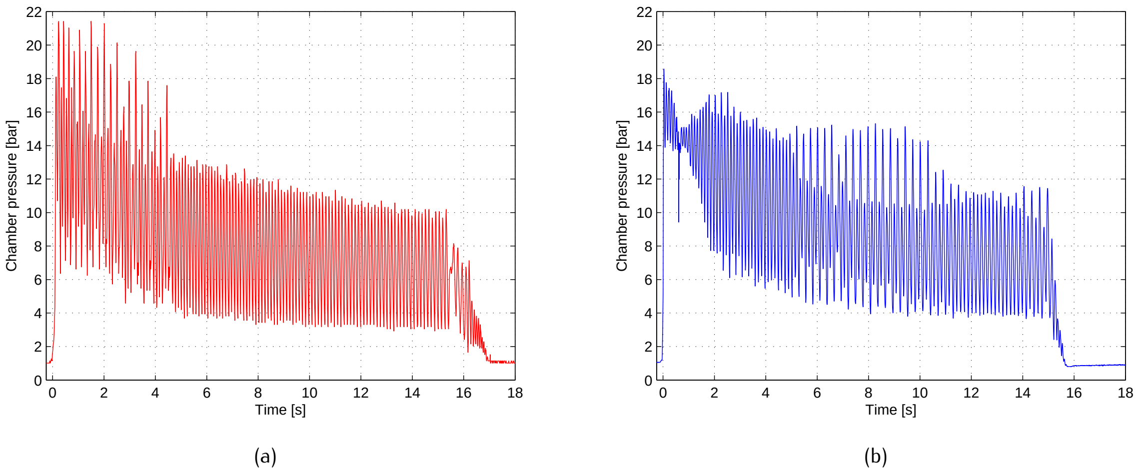
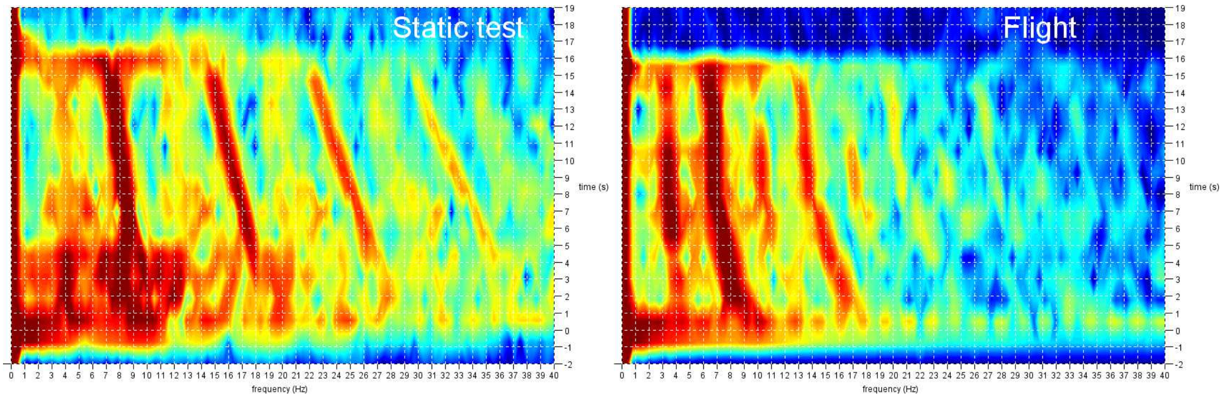


Figure 2.1: (a) Combustion chamber pressure during static test. (b) Combustion chamber pressure during flight.

Low pass filtered version of the combustion chamber pressure and the LOX tank pressure form both static test and flight are shown in Fig. 2.3(a). From this it is possible to calculate the thrust from the flight motor as

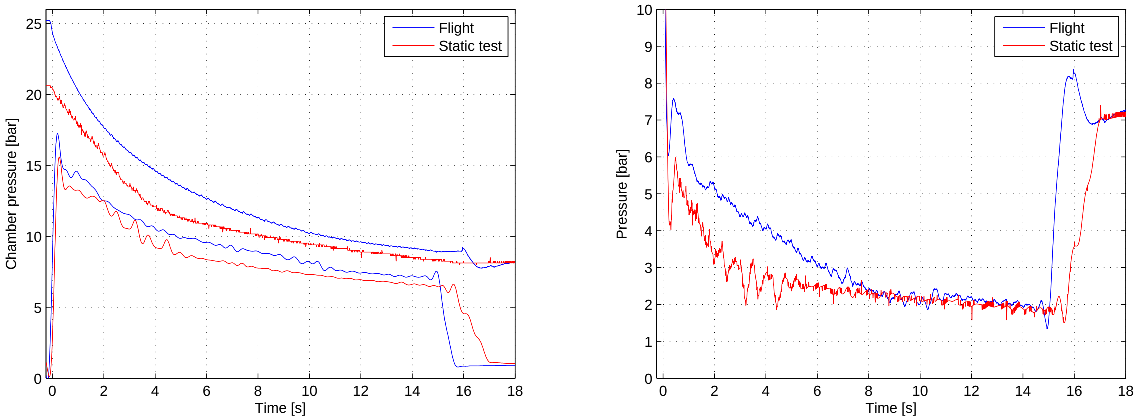
$$F = A_t k p \tag{2.1}$$

where A_t is the nozzle throat area, k is the thrust coefficient and p is the combustion chamber pressure. The thrust coefficient is assumed to be $k = 1.2$ and hence the maximum thrust at lift off can be calculated to be around 75 kN. Thrust falls of with time and is about 30 kN at MECO.



(a) (b)

Figure 2.2: (a) Combustion chamber pressure spectrum during static test. (b) Combustion chamber pressure spectrum during flight.



(a) (b)

Figure 2.3: (a) Low pass filtered plots of the combustion chamber pressure and LOX tank pressure during flight and the static test. (b) Injector pressure drop for flight and static test.

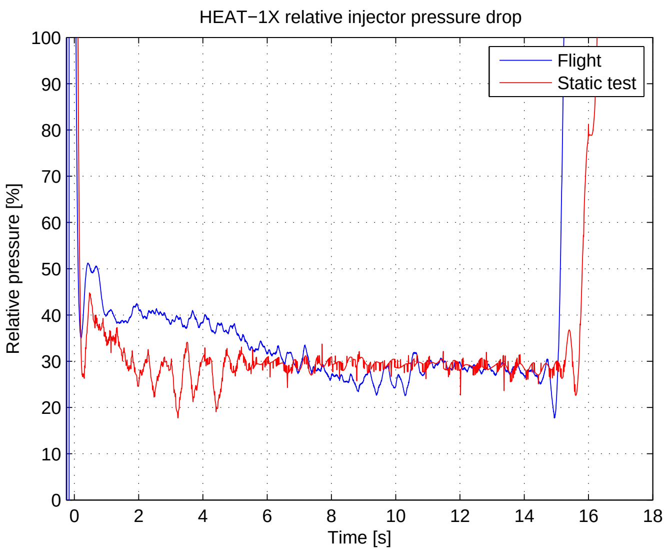


Figure 2.4: Injector pressure drop relative to chamber pressure.

3 Flight performance

3.1 Introduction

For flight analysis two different coordinate systems are used. The onboard computer in Tycho works in the coordinate system illustrated in Fig. 3.1(a). The sensor inputs are then used to calculate parameter values in a coordinate system relative to Sputnik as illustrated in Fig. 3.1(b). The two coordinate systems will be referred to as onboard and global coordinate systems.

As the uncertainty of the onboard inertial system increases with time to the power of three and due to the high forces experienced at separation (see section 3.4 for details) the data acquired after separation are associated with some error. After landing the horizontal velocity is measured to be 44 m/s and the altitude is measured to be 130 meter. Both values should be zero and this is of course a result of the accumulated error. Thus, the reader should bear in mind that data after separation (T+32) might have a significant error to it.

3.2 Acceleration and speed

The acceleration measured by the onboard computer system is plotted in Fig. 3.2(a). The high amplitude oscillation from the booster is naturally also present in the accelerometer data. The actual acceleration of the vehicle is plotted in 3.2(b) in global coordinates. The maximum acceleration recorded is while the vehicle is still on the launch rail and is 43 m/s^2. As the vehicle pithes over the z-component of acceleration drops and is only about 3 m/s^2 for the last half of the powered flight. Instead the vehicle has a significant horizontal acceleration until MECO at T+15.1.

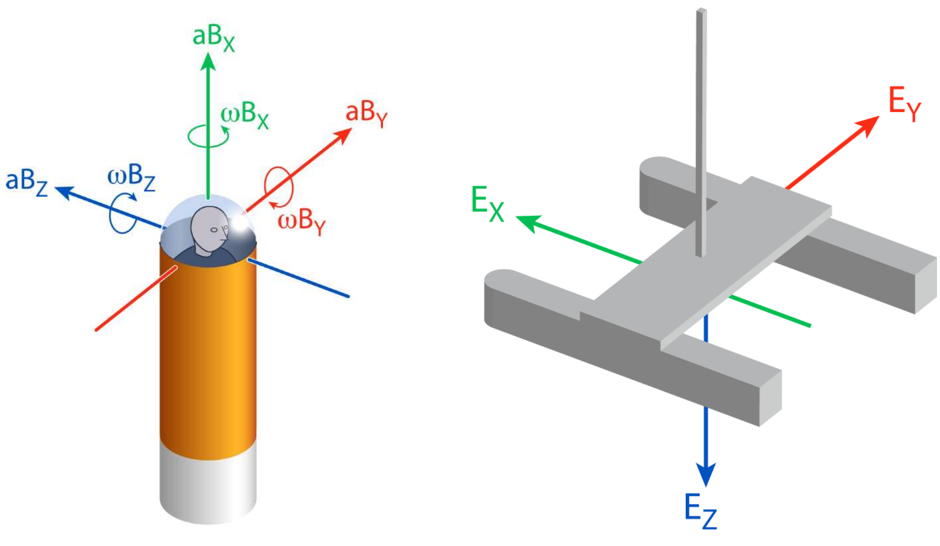


Figure 3.1: (a) Definition of coordinate system onboard Tycho Brahe. (b) Coordinate system relative to Sputnik.

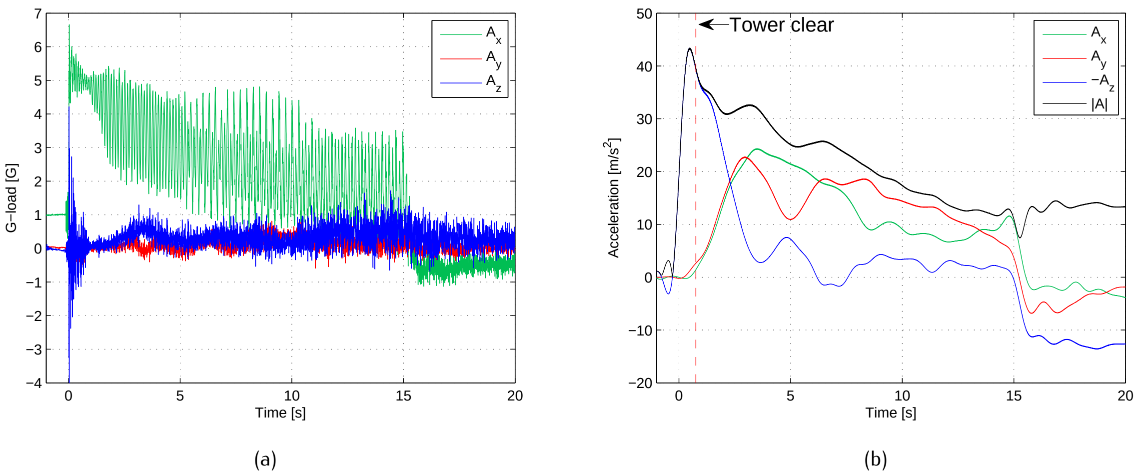


Figure 3.2: Accelerometer readings (including 1G from gravity) as a function of time in onboard coordinate system. (b) Vehicle acceleration as a function of time, global coordinate system.

The velocity in the global coordinate system is plotted in Fig. 3.3(a). The highest recorded speed is 300 m/s at MECO. The highest z-velocity is 117 m/s and the highest horizontal velocity (seen in Fig. 3.3(b)) is 277 m/s. Separation between booster and spacecraft happens at T+31.7 with a speed of 223 m/s.

The downrange distance is also plotted on the right axis of Fig. 3.3(b). At separation the vehicle is already 6300 meters downrange. As stated earlier the error increases rapidly after separation and thus the plotted downrange value is not correct towards the end of the data. With reference to Fig. 3.3 the error seems to be largest on the x-axis, at least both the y- and the z-axis ends up close to zero after landing.

3.3 Pitch, roll and altitude

The pitch and the pitch rate are both plotted in Fig. 3.4(a). In a matter of just 1.2 second, from the vehicle clears the tower at T+0.76 it achieves a pitch rate of -30°/s. At T+3.6 the pitch angle is 30° and for the remaining part of powered flight the pitch angle stays around 30°. This is investigated in more detail in section 3.5.

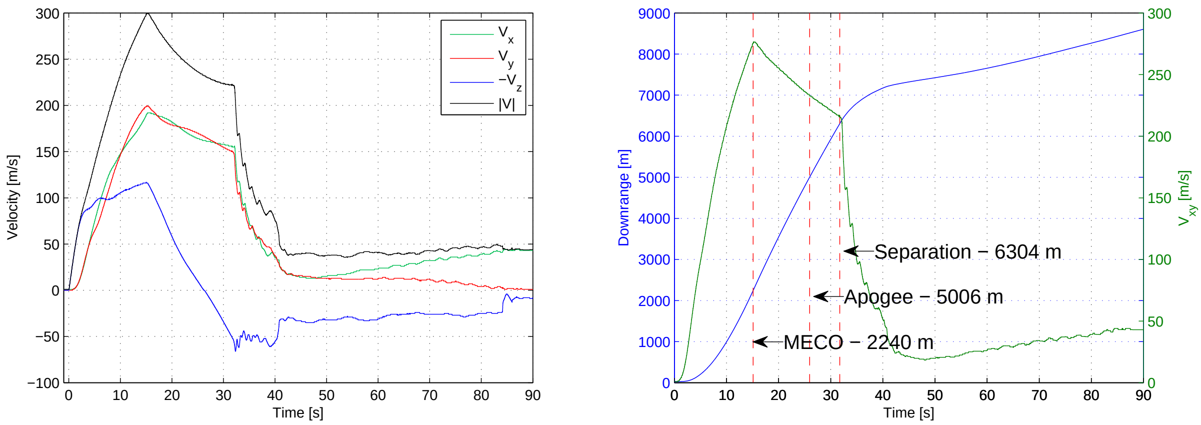
The roll angle, θ, and the roll rate are plotted in Fig. 3.4(b). The roll angle is plotted as the cosine to the roll angle relative to the initial angle. Thus it starts out at 1 and a 90° roll corresponds to a value of 0 and so forth. Initially the vehicle rolls from side to side but from T+5 it only rolls in one direction. From T+5 to separation the average roll rate is 27°/s and the vehicle completes two full revolutions from lift off until separation.

The altitude as a function time is plotted in Fig. 3.5. MECO occours at T+15.1 at an altitude of 1411 m and from then the vehicle coasts to react apogee at T+26.2 at an altitude of 2021 meters.

Separation occurs 5.76 s after apogee at an altitude of 1883 m.

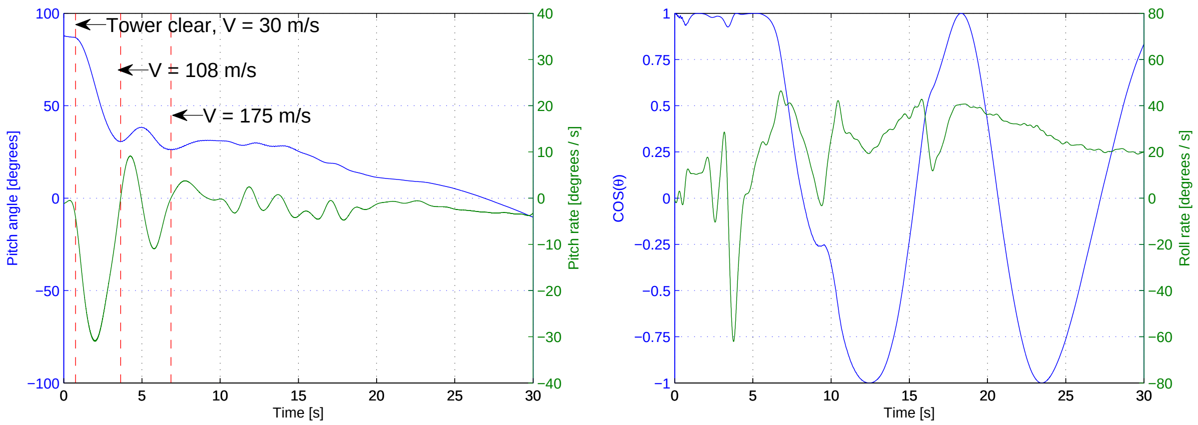
3.4 G-load at separation and impact

Due to the close to horizontal trajectory of the vehicle separation occurred at a quite high horizontal speed of 223 m/s. Immediately after separation the booster and spacecraft starts to tumble. Due to the high speed this gives rise to a large force and rapid acceleration of the spacecraft. The G-load of the spacecraft at separation is seen in Fig. 3.6(a). A maximum load of 17 G is recorded. Impact with the water is significantly more violent but the event only lasts about 150 ms. The G-load at impact is seen in Fig. 3.6(b). A maximum load of 29 G is recorded.



(a) (b)

Figure 3.3: (a) Velocity as a function of time. (b) Distance from launch position and V_{XY} as a function of time.



(a) (b)

Figure 3.4: (a) Pitch and pitch rate as a function of time. (b) Left axis: Roll angle as a function of time. Right axis: Roll rate as a function of time.

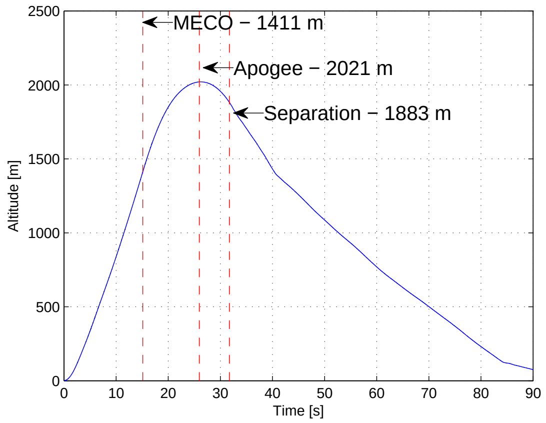


Figure 3.5: Altitude as a function of time.

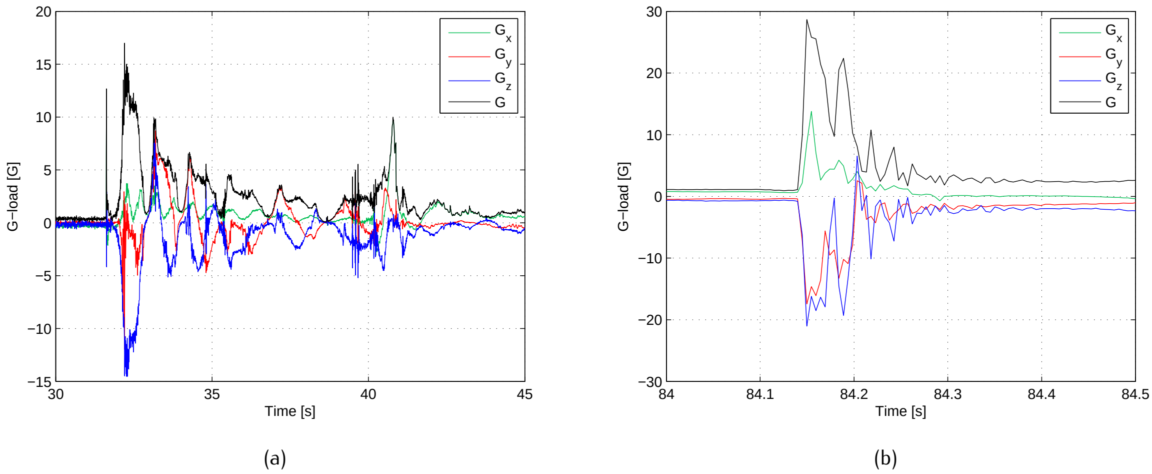


Figure 3.6: (a) G-load at separation and (b) G-load at impact.

3.5 Pitch analysis

As stated earlier the vehicle pitches over immediately after clearing the launch tower. The pitch angle and pitch rate are plotted in Fig. 3.4(a). According to the position data the tower is cleared at T+0.76. However, the pitch rate at this time is already -4 °/s indicating that the pitch started at an earlier time. The pitch and pitch rate from T+0.5 to T+1 are plotted in Fig. 3.7. The pitch rate is zero at T+0.65 and then starts to decrease from this point, suggesting that the pitch motion starts at this time while the vehicle is still in contact with the launch tower. The pitch angular acceleration is fairly constant from T+0.65 to T+1.7 and is about 30°/s^2 or 0.5 rad/s^2. The moment of inertia of the vehicle at lift off is estimated to be I = 11250 kg/m^2 (m = 1630 kg and l = 9.20 m). Thus, the torque working on the vehicle is about 5600 Nm. At T+3.6 the pitch is about 30° and remains at this level until MECO. This raises a few important questions:

- What gives rise to the initial torque of 5600 Nm?
- Why does it stop at about T+3.6?

Our analysis indicates that the initial torque is due to a misalignment of the thrust vector which in turn is most probably due to a misaligned nozzle. The misalignment is illustrated in Fig. 3.8 where the jet is misaligned about 1.2° to the booster. From the still image the angle is measured to be about 1.2 degrees. It is likely that the angle is larger than this since one will only see the actual angle in a picture taken at 90 degrees to the pitch plane. At T+0.76 the thrust from the motor is estimated to be 61 kN. The nozzle throat is positioned 282 cm behind the center of gravity. Thus the torque provided by this misalignment is 3600 Nm. This is not enough to account for the observed torque of 5600 Nm. For nozzle misalignment to account for the observed torque the actual angle has to be 1.9°. This could also very well be the case as the 1.2° measured on the image is a minimum.

The next question is then, if a misaligned thrust vector provides enough torque to turn the vehicle, why does it then stop at about T+3.6? The answer lies in Fig. 3.9. This figure shows the pitch of the actual path the vehicle is traveling and it shows the accumulated roll of the vehicle (right axis).

Initially the attitude pitch of the vehicle drops faster than the path pitch, this gives a large angle of attack on the fins. As the vehicle gains speed the correcting force from the fins increases and at about T+3.6 at a speed of 108 m/s the torque provided by the fins becomes large enough to force

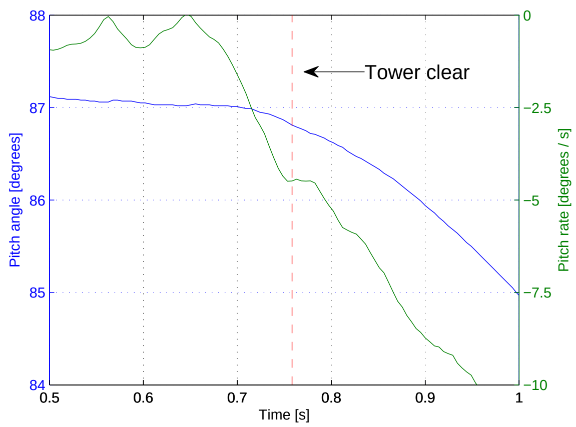


Figure 3.7: Pitch and pitch rate as a function of time as the vehicle clears the tower.

the vehicle to level out. At T+7.9 the vehicle has rolled 90° and thus the misaligned nozzle now produces a torque pitching the nose up. At the same time the angle of attack changes sign, i.e. the attitude pitch becomes higher than the trajectory pitch. From T+7.9 to T+12.2 the vehicle rolls an additional 90° and the misaligned nozzle now produces a torque pitching the nose up. After MECO the trajectory pitch and the attitude pitch lies within a few degrees.

Figure 3.8: Still image from the launch showing the exhaust flame at an angle of 1.2° to the vehicle.

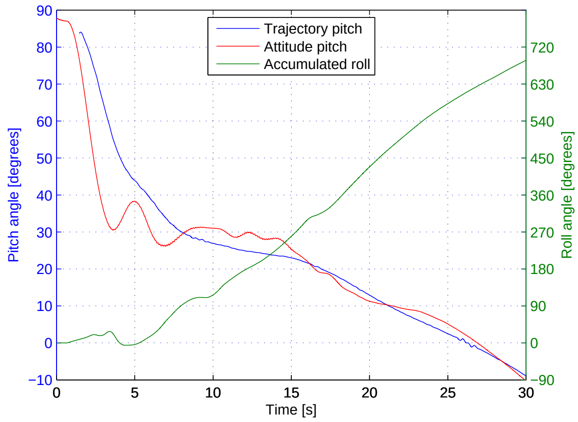


Figure 3.9: Attitude pitch, trajectory pitch and accumulated roll as a function of time.

3.6 Comparison with doppler radar data

Weibel Doppler Radars generously supplied an advanced doppler radar system and a two man crew to operate it. The radar was positioned on the deck of Hjortø. Thus, Hjortø both served as mission control ship and as a radar platform. This posed a trade off. From a tracking point of view the distance between radar and rocket should be fairly large such the the slew rate of the radar gantry could be kept small. For optimal reception of radio and video feed from Sputnik the distance should however be relatively small. A distance between Sputnik and Hjortø of 3 km was chosen as a compromise.

As described earlier HEAT-1X took an undesirable flight path after lift off. In fact, it flew more or less in the direction of Hjortø. The combination of short distance between rocket and radar and the rising and also approaching rocket was a worst case scenario from a radar tracking perspective. It put the radar gantry hard at work keeping track of the rocket and as the gantry reached its maximum elevation tracking was lost. For future missions any radar setup should preferably be positioned on land to avoid this.

To validate the precision of our custom made onboard flight computer the altitude measured by Weibel is compared to the altitude measured by the onboard computer. The measured altitude from both are plotted in Fig. 3.10. At the last point of radar tracking the greatest difference is found and it is 50 m out of 1850 m, this corresponds to a difference of less than 3%.

The data supplied by Weibel is available as a plot in Google Earth, download the KMZ file here: `http://www.copenhagensuborbitals.com/public/110603_0016trans_2.kmz`

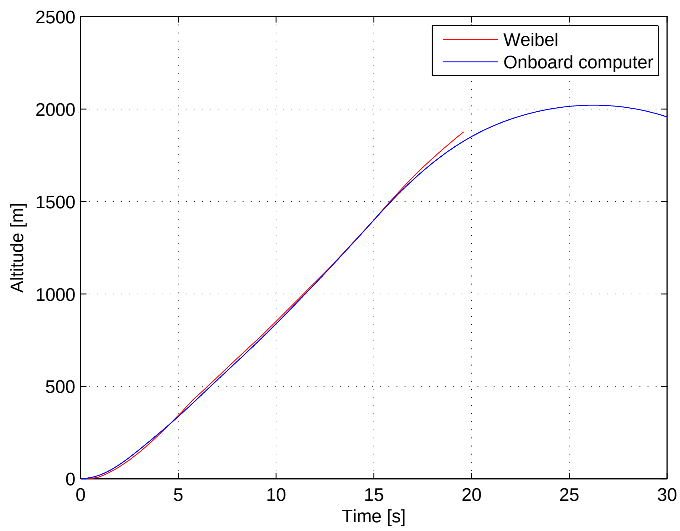


Figure 3.10: Comparison of the altitude as measured by Weibel and the onboard flight computer.

4 Conclusions

4.1 Conclusions

First of all, the Copenhagen Suborbitals 2011 Launch Campaign has been a tremendous success! CS has proven itself capable of building a 12 ton heavy mobile launch facility and launch a 1630 kg, 9.38 meter tall rocket from sea. This is a milestone in CS's program to reach manned suborbital spaceflight. Launching a rocket this size is however not only about technological ability. It is also about building up a strong organization which is recognized by authorities and partners as a serious project. Thus, both technological and organizational experience from the 2011 LC will provide a solid platform for future launches.

The undesirable trajectory forced a premature motor shutdown. The shutdown was performed by radio control and the decision to do so was made based on downlinked trajectory information and real time trajectory interpolation and impact prediction. It is the first time in aviation and space flight history that a rocket flight is safely aborted in this way. This feature demonstrates CS's commitment to range safety and safety to CS and other participating personnel.

Based on the data measured during flight a number of important conclusions are made. Most significantly the cause of the pitching motion seems to have been identified as a misaligned nozzle. Unfortunately it will never be possible to verify this as the booster disintegrated on the high speed impact with the water.

Comparison of doppler radar data with data from the onboard flight computer indicate that the onboard system has an high accuracy during powered flight.