THE FLIGHT CONTROL OF SHEFEX II

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1 NOMENCLATURE

ACS	Attitude Control System
DCTA	Departamento de Ciência e Tecnologia Aerospacial
DLR	German Aerospace Center
GPS	Global Positioning System
IIP	Instantaneous Impact Point
IMU	Inertial Measurement Unit
RADAR	Radio Detecting and Ranging
SHEFEX	Sharp Edge Flight Experiment

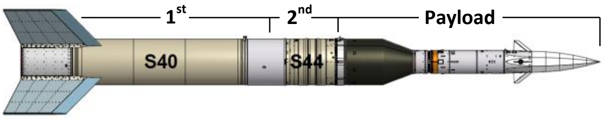
2 ABSTRACT

SHEFEX II (Sharp Edge Flight Experiment) was a two-stage sounding rocket mission to investigate advanced reentry technology. The successful launch was conducted from Andøya Rocket Range, Norway in June 2012. Comprising a suppressed trajectory, initiated by a cold-gas pointing maneuver prior to 2nd stage ignition, and spanning 800 km over the Norwegian sea, it was the most complex sounding rocket mission ever carried out by the German Aerospace Center DLR. To maximize the chances of a mission success, a mission scenario was developed that accounted for system failures and permitted to compensate for them or at least tolerate them long as no safety limits were infringed. The actual flight proved these measures very effective. A strong deviation of the unguided 1st stage from its nominal trajectory could be successfully compensated for by the flight control of the 2nd stage. This resulted in a nominal mission sequence and payload impact in immediate proximity of the nominal aiming point.

3 INTRODUCTION

3.1 Vehicle and Mission Objective

The scientific mission objective was to flight-test the behavior of a variety of advanced reentry technologies during a flat reentry at Mach 10. The rocket motors, S40 and S44, were solid propellant motors of the composite type, developed and manufactured by DCTA Brazil.



Property	Units	Value
Payload Mass	[kg]	707.9
S40 Propellant Mass	[kg]	4320.0
S44 Propellant Mass	[kg]	810.0
Total Vehicle Mass	[kg]	7057.6
Total Vehicle Length	[m]	12.76
S40 Burn Duration	[s]	54
S44 Burn Duration	[s]	63

Figure & Table 1. Characteristic Vehicle Properties.

3.2 Nominal Mission Sequence

The nominal mission sequence starts with the fin stabilized ascent of the first stage, rail-launched at a nominal elevation of 82.5 ° as a compromise between gaining as much horizontal velocity as possible for a flat reentry and keeping structural loading and aerodynamic drag losses low during the atmospheric crossing. In the interest of dispersion reduction, the fins were set at an incidence angle of 0.6 ° to impart a final spin rate of 1.5 Hz around the longitudinal axis of the vehicle. Upon reaching the upper end of the relevant atmosphere at 85 km, the burnt out 1st stage booster is jettisoned. To maximize the duration of the experiment conducted on the reentry part of the trajectory, a shallow reentry flight path is then initiated by a cold gas pointing maneuver that takes the vehicle attitude down to 38.1 ° in elevation (over local ellipsoid) prior to ignition of the 2nd stage rocket motor. The experiment itself is carried out at Mach numbers around 10, in the altitude layer ranging from 100 km down to 20 km, where the payload is split in two halves and recovered by parachute. The touch down is located 800 km down range at an azimuth bearing of 346 °.

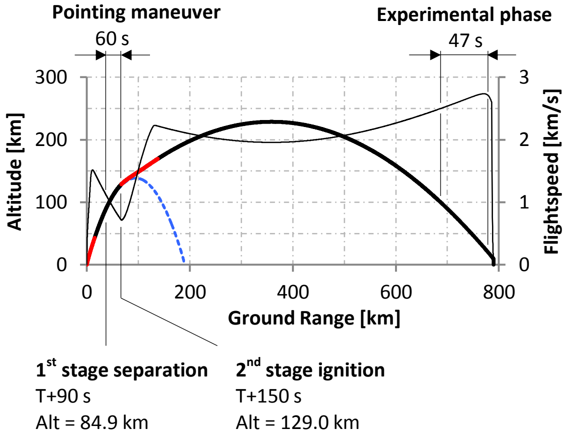


Figure 1. Nominal trajectory (thrust phases in red, S40 booster trajectory in blue)

4 KEY ELEMENTS

4.1 Failure Tolerant Mission Design

The cold gas attitude control system to conduct the pointing maneuver had specifically been developed for SHEFEX II, and is a particularly complex system, as it controls the vehicle attitude while spinning at 1.5 Hz. Novelty and complexity make the occurrence of a system failure a probable scenario. To maximize the chances of mission success, system malfunctions were accounted for and could - to a certain degree – be tolerated due to a robust mission outlined in the following.

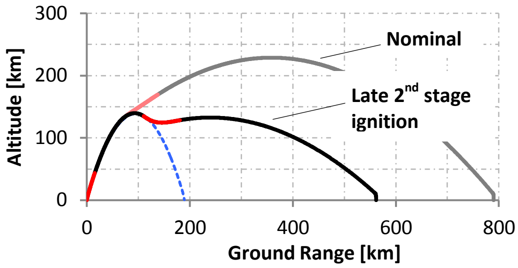


Figure 2. Nominal ascent trajectory with latest permitted 2nd stage ignition

The nominal mission sequence dedicated a 60 s timespan to the pointing of the vehicle in the coast phase after 1st stage separation. This comprised the calculation of the pointing angles after the atmospheric crossing, the tele-command operation to the vehicle and the actual pointing maneuver and is just sufficient in case the attitude control system works nominally. In case of a system failure resulting in a slower or erratic operation, the coast phase could be extended up to 140 s in order to improve the vehicle pointing. Fig. 2 depicts the trajectory shape resulting from such a "latest ignition" case while assuming all other flight parameters nominal. Any later ignition of the 2nd stage was not permitted because of the risk to re-enter the atmosphere with the 2nd stage still burning, which would inevitably result in the loss of the mission, as the 2nd stage is not aerodynamically stable.

To cover the case where the desired pointing angles cannot be reached by the system, it was foreseen to continue the mission anyways, provided that the actual pointing resulted in an impact within the conceded impact area and would not lead to the 2nd stage burning within the atmosphere. This also included the circumstance, in which the attitude control system would not work at all and the 2nd stage would be lit at the angle the vehicle left the atmosphere. In all these cases, the experiment could still have been conducted and valuable scientific data gathered. However, the resulting impact point would have been located far from nominal. Therefore the conceded impact area notified by Andøya Rocket Range was chosen as large as possible (extending 830 km in north-south and 760 km in east-west direction) while avoiding frequented ship and air traffic routes, see Fig.3.

4.2 Dispersion Reduction

The cold gas pointing maneuver accomplished prior to 2nd stage ignition was also exploited to reduce the impact point dispersion. Dispersion analysis [3] shows, that the major fraction of the impact point dispersion, roughly 90 % in area, is induced during the atmospheric ascent and 1st stage burn. A proper correction of the pointing attitude prior to 2nd stage ignition therefore permits to compensate for any deviation from the nominal trajectory, and hence reduce the 3-σ impact dispersion down to an ellipse of a half axes magnitude of 23 x 80 km, see Fig 3.

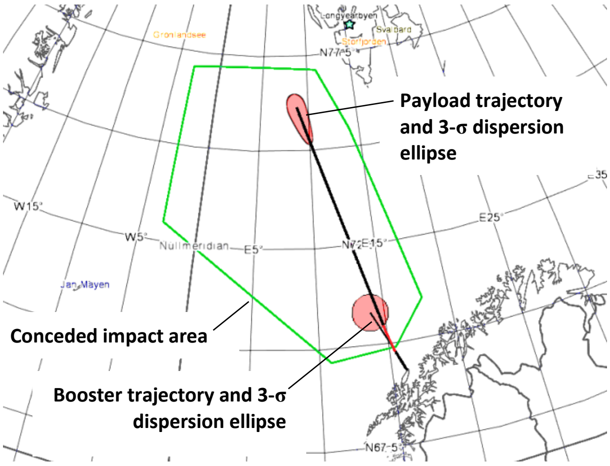
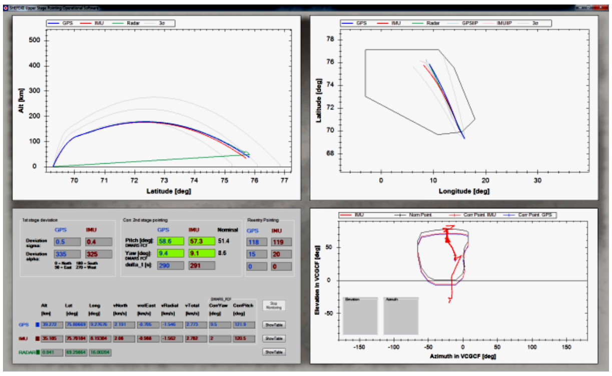


Figure 3. Map view on nominal trajectory, booster trajectory, 3-σ impact areas and conceded impact area

An algorithm was developed, that generates the corrected pointing angles for the 2nd stage and is described in detail in [3]. It was implemented in the ground segment to provide the required computing power and also to allow for a human control of the pointing angles finally commanded to the attitude control system. The algorithm core is a linear-quadratic function of the actual deviation in position and velocity from the nominal trajectory after 1st stage burn out and atmospheric crossing. The position and velocity data required are extracted from either of the telemetry streams of the on board GPS and IMU units, therefore granting a single fault redundancy in case of a malfunction of one system.

4.3 2nd stage burn monitoring & thrust termination

Because of the involvement of an active attitude control on the 2nd stage, a possibility to terminate the 2nd stage thrust phase in case of a critical system malfunction became an essential requirement to safeguard the uninvolved public. To support a quick decision on the mission health, a software application was developed that allowed to monitor the vehicle position and instantaneous impact point (IIP) derived from all available trajectory data sources (GPS, IMU and RADAR) in close to real time. All curves and values on its single screen display are color-coded according to the data they are based on (blue = GPS, red = IMU, green = RADAR). This and the simplicity of the display ease an all-time situational awareness of the Flight Safety Officer.



1st stage deviation

	GPS	IMU
Deviation sigma:	0.5	0.4
Deviation alpha:	335	325

0 = North 180 = South
90 = East 270 = West

Corr. 2nd stage pointing

	GPS	IMU	Nominal
Pitch [deg]: DMARS FCF	58.6	57.3	51.4
Yaw [deg]: DMARS FCF	9.4	9.1	8.6
delta_t [s]:	290	291	

Reentry Pointing

GPS	IMU
118	119
15	20
0	0

Figure 4: In-flight display of safety software

4.3.1 Flight Termination Regime

The possibility to terminate the 2nd stage burn was realized by an explosive load mounted along the motor case of the S44 rocket motor that could be activated by tele-command.

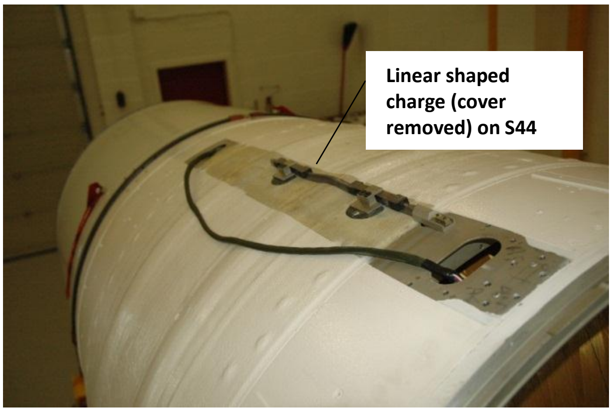


Figure 5: Linear shaped charge on 2nd stage

As destructing the hull of the thrusting motor would likely have resulted in a damage of the payload, this was considered only a last resort in the following cases:

A) Unacceptable uncertainty of the IIP

This is when no, not enough, or not trustworthy IIP or position data are available within the first 20 s of 2nd stage burn to indicate that the vehicle strides away from the mainland. 20 s was chosen as a “green time” because this is about the minimum time it takes – in the worst case that the 2nd stage points backwards - for the IIP to reach the Norwegian mainland.

B) Unacceptable IIP path

This is when the IIP infringes the conceded impact area depicted in Fig. 3.

5 FLIGHT RESULTS

GPS and IMU data were available through all critical flight phases and in good conformance until the end of 2nd stage burn.

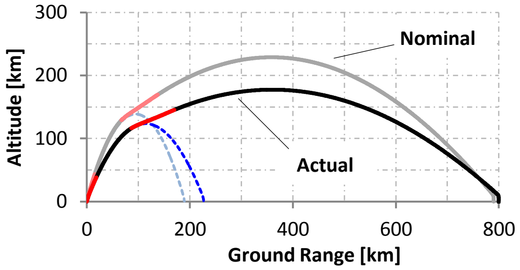


Figure 6. Actual trajectory of SHEFEX II vs. nominal trajectory. Actual from GPS data. Booster downleg and last 25 km of payload trajectory reconstructed by trajectory fitting.

The 1st stage trajectory deviated significantly from nominal, with the impact located 43.7 km downrange of the Nominal Aiming Point (= 2.5 σ) as illustrated in Fig. 6. In a post-flight analysis, this was found to be due to an overdamped aerodynamics modeling, leading to an underestimation of the influence of the launcher tip-off effect on the trajectory.

The deviation was detected by the dispersion reduction algorithm – based on GPS flight data – which proposed to lower the vehicle elevation prior to 2nd stage ignition by 7.2 ° to 30.9 °. The pointing angles were tele-commanded to the vehicle and the flawlessly working attitude control system redirected the vehicle within the nominal 60 s coast phase.

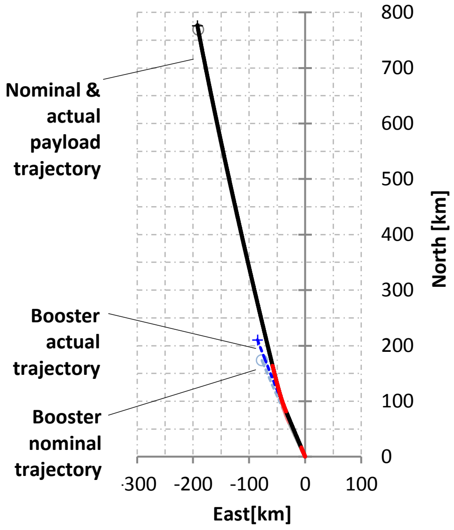


Figure 7: Actual and nominal trajectory ground tracks. Actual payload ground track in perfect conformance with nominal.

The 2nd stage was ignited at the nominal T+150 s. Impulse generated by the S44 was close to nominal and the attitude of the spin stabilized stage stable within a tolerance of ± 1 °. The reentry phase also elapsed close to nominal until loss of the telemetry link in 25 km altitude. The actual touch down of the payload occurred 8.5 km north of the nominal aiming point. Therefore, the mission was considered an outstanding success, especially in view of the complexity and novelty of its mission scenario.

6 REFERENCES

1. Cremaschi, Weikert, Wiegand, Scheuerpflug, Sounding Rocket Trajectory Simulation and Optimization with ASTOS, Proceedings of the 19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, 2009
2. Scheuerpflug, Dragøy, SHEFEX II Flight Safety Rationale V1.3, Oberpfaffenhofen, June 2012
3. Scheuerpflug, Kallenbach, Cremaschi, Sounding Rocket Dispersion Reduction by Second Stage Pointing Control, Journal of Spacecraft and Rockets, Vol.49, No.6, Nov-Dec 2012
4. Weihs, Longo, Turner, The Sharp Edge Flight Experiment SHEFEX II, a Mission Overview and Status, Proceedings of the 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2008
5. Turner et al., SHEFEX II Development Status of the Vehicle and Sub-Systems for a Hypersonic Re-Entry Flight Experiment