Main Achievements of the Rocket Technology Flight Experiment ROTEX-T

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Based on experience gathered during the hypersonic flight experiments SHEFEX-I and SHEFEX-II the German Aerospace Center (DLR) performed the extensively instrumented flight experiment ROTEX-T (ROcket Technology EXperiment-Transition). ROTEX-T was successfully launched on 19th July 2016 at 06:05 am CEST from the Esrange Space Center near Kiruna in northern Sweden. Students of the RWTH Aachen University supported the design of the project with numerical simulations. ROTEX-T was a low cost flight experiment mission without inertial measurement unit, reaction control and parachute system. The payload reached an altitude of 183 kilometers, performed a ballistic re-entry with a total flight time of approximately 446 seconds and was afterwards recovered by helicopter. An unique and modular data acquisition system with sampling rates of 20 Hz, 1 kHz, 10 kHz and 2000 kHz was developed for ROTEX-T to study also instationary aerothermal phenomena.

Nomenclature

H	=	altitude, km
IMU	=	Inertial Measurement Unit
L	=	characteristic length, m
m	=	mass, kg
M	=	Mach number, -
p	=	pressure, mbar
q	=	dynamic pressure, mbar
RCS	=	Reaction Control System
Re	=	Reynolds number, -
ROTEX-T	=	Rocket Technology Experiment-Transition
T	=	temperature, K
t	=	time, s
v	=	flow velocity, $m \cdot s^{-1}$
x, y, z	=	coordinates, m

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I. Introduction

Low cost access to space requires efficient and reliable design tools to reduce the design margins to a minimum. Although ground testing still provides the main design verification, a complete simulation of the flight conditions is usually not possible. Therefore flight experiments are the most effective tool to obtain validation data under real flight conditions. The flight data can then be used to validate and improve analysis and design tools for future missions.

As the flight environment is complex and the flight trajectory has almost a continuous transitional character, the corresponding instrumentation and data acquisition system have to be designed accordingly. The response time of the sensors has to be minimized while the sampling rate should be as high as possible. Furthermore, hypersonic flight experiments should demonstrate the flight Technology Readiness Level (TRL) of key technologies and gather data for a better understanding of flight physics. Since parameter studies during high speed flight experiments are extremely limited, complementary use of ground testing facilities and Computational Fluid Dynamics (CFD) is essential.

In order to gain flight data in hypersonic flight regimes DLR successfully performed the sharp edged hypersonic flight experiments SHEFEX-I[1] and SHEFEX-II[2,3,4,5]. Compared to SHEFEX-I, which reached Mach numbers up to 6.5, SHEFEX-II achieved a maximum Mach number of 9.3 and was equipped with a higher numbers of sensors including a new type of Flush Airdata Sensing (FADS) system for the sharp edged configuration. Based on this experience DLR performed the flight experiment ROTEX-T (ROcket Technology EXperiment-Transition) which was extensively instrumented with pressure, temperature and heat flux sensors. ROTEX-T was successfully launched on 19th July 2016 at 06:05 am CEST from the Esrange Space Center near Kiruna in northern Sweden.

Chapter II and III of this paper describe the ROTEX-T flight configuration and its instrumentation. The flown trajectory including main flight parameters is presented in chapter IV together with some results of the measured pressure and heat flux distribution. Finally, the main outcomes of the experiment are summarized in chapter V.

II. Flight Configuration and Integration

The complete flight configuration with a length of 10 meter on the launch pad is shown in Fig 1. The ROTEX-T payload was launched on a two-stage unguided rocket motor configuration. The first stage consisted of the solid propellant motor Terrier Mk12 and for the second stage an Improved Orion (mil. M112 Hawk) motor was used, which is also driven by solid propellant. The Terrier motor has a burn phase of 5 seconds. The Improved Orion motor is a dual thrust burner with a boost phase of 5 seconds and a sustainer phase of approximately 21 seconds. During the complete acceleration phase of approximately 40 seconds a peak acceleration of about 19.4 g is reached.

Figure 1. ROTEX-T complete configuration at the launcher.

Figure 2. ROTEX-T payload mounted to second stage.

The overall length of the payload including all service modules and motor adapter was 3.013 m with a diameter of 356 mm. This led to a total payload mass (including motor adapter and balance masses) of about 190 kg. Fig. 2 shows the payload mounted to the second stage motor on its way to the launch pad. The front part of the payload consisted of a cone with a half angle of 7° and a length of 1041 mm. A conical flare with 20° deflection angle and a length of 132 mm was attached to the cone. To measure key aerothermal parameters during flight these two parts, which represent the main scientific part of the payload, were instrumented with a large number of sensors. Behind the conical flare two experiment service modules with a length of 400 mm each were used containing the necessary electronic boxes for data acquisition. The first service module was also equipped with several heat flux and pressure sensors. The complete payload layout is shown in Fig. 3.

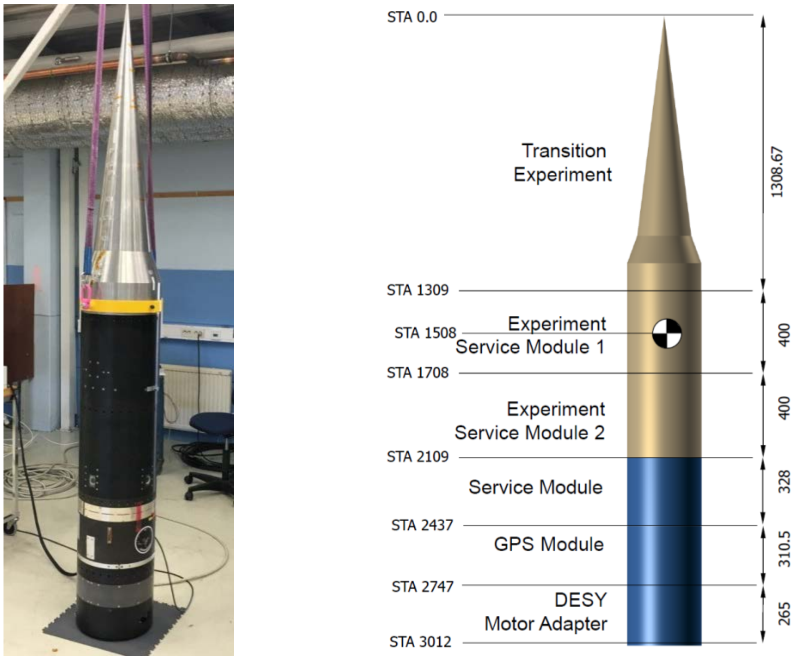

Figure 3. ROTEX-T payload overview.

The 7° stainless steel cone consisted of two halves for easier instrumentation. To avoid screw connections on the outer surface, the two halves were joined together using a dovetail connection. Due to the very precise manufacturing of the dovetail connection no steps or gaps were visible between the two halves after assembly. The first part of the cone was manufactured as a separate solid part, because it was not possible to manufacture the dovetail connection to the very tip of the cone halves. This nose part with a length of 141 mm and a nose radius of 2.5 mm also acted as a fixation "ring" for the two cone halves. As the highest temperatures occur at the nose tip, the nose part was manufactured from high temperature steel INCONEL 600.

The 20° conical flare part, which was made from stainless steel, also consisted of two halves for better instrumentation. Because more space for mounting was available inside this part, the two halves were joined by eight M6 screws which were located internally and no dovetail connection was necessary. But a tongue-and-groove joint was manufactured between the two halves that acted as a kind of sealing. After the instrumentation was completed, the 20°-flare part was mounted to the 7°-cone by twenty M8 screws.

Nearly all sensors were thereby mounted via simple screw connections. Only the cylindrical PCB pressure sensors were glued into boreholes with high temperature silicone. For routing the harness of sensors and electronic boxes several cable guides were installed in the interior. The cable guides were located near the axis of the vehicle to prevent the cables coming in contact with the hot wall during flight.

Beside the main electronic boxes for data acquisition, located in the experiment service modules, several small front-end electronic boxes were necessary for the high-speed data acquisition systems (10 kHz, 2000 kHz). These boxes were placed inside the cone and flare parts near the sensors for sensor signal amplification and analog-digital conversion. The digitized sensor signals were then sent to the main electronic box in the first experiment service module. The front-end electronic boxes and the cable guides can be seen in Fig. 4 where the cone halves are shown during instrumentation.

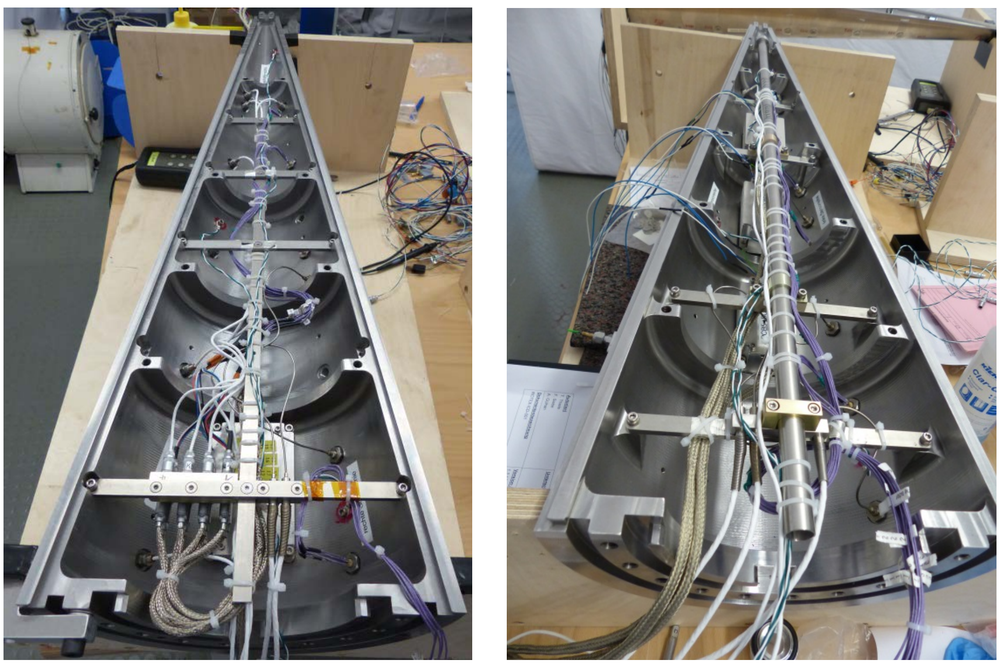

Figure 4. ROTEX-T 7°-cone halves during instrumentation.

The two experiment service modules were manufactured from black anodized Aluminium. The first service module contained the high-speed data acquisition system used for PCB and Kulite pressure sensors and coaxial-thermocouples. This system, integrated into a cylindrical housing and mounted to an Aluminium bulkhead, also included a crash resistant memory which was necessary, because not all data could be transmitted to the ground station due to the high sampling frequency and limited telemetry bandwidth. The second experiment service module contained the low-speed data acquisition system (20 Hz), the medium-speed (1 kHz) and fiber optic data acquisition systems both including a crash resistant memory in two separate boxes and four HD-cameras including their support structure. The umbilical connector, used for payload testing after assembly, was also integrated into the second service module. The experiment service modules were mounted together by a so-called RADAX joint, which was also used for the connection between flare-part and first experiment service module. The joint consists of thirty M5 screws equally spaced every 12° in circumferential direction. The first and second experiment service modules during assembly are presented in Fig. 5.

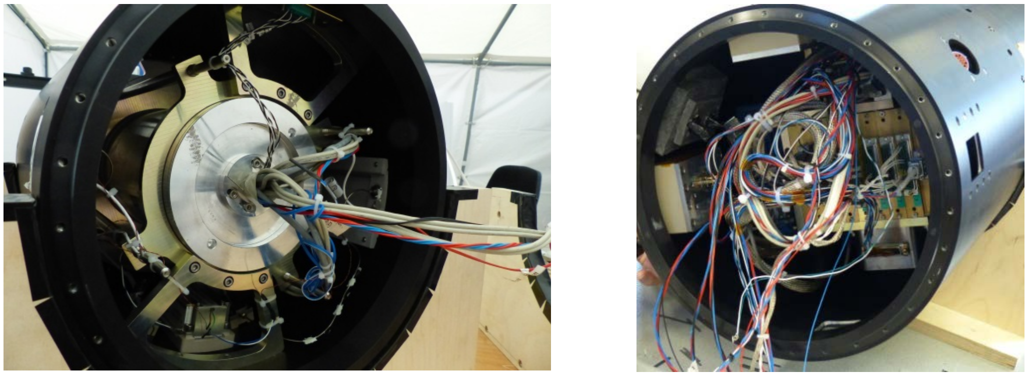

Figure 5. First (left) and second (right) experiment service modules during integration

In addition to the two experiment service modules another service module, a GPS module and a motor adapter were part of the payload (see blue marked modules on the right side of Fig. 3). The service and GPS module contained the batteries, the telemetry transmitter, the GPS system receiver, the wrap around antenna for GPS and the necessary ignition unit for vehicle time events (e.g. ignition 2nd stage, Yo-Yo de-spin and payload separation). The motor adapter, which also included the de-spin system (Yo-Yo de-spin), served as interface between payload and second stage motor.

Beside the instrumentation of the payload itself (cone and flare parts) one of the second stage fins and the tailcan of the second stage were also instrumented with thermocouples and strain gauges. The two necessary small electronic boxes were mounted to the interior of the tailcan as shown in Fig. 6.

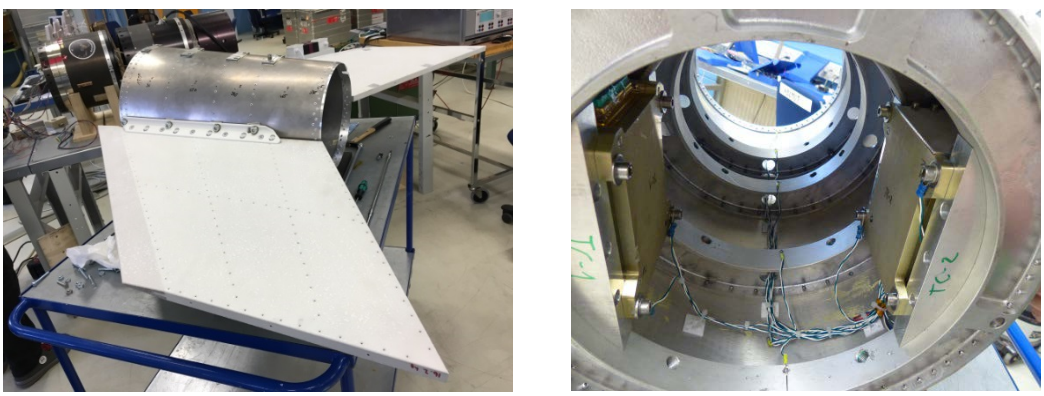

Figure 6. Fin integration to tailcan (left) and electronic boxes mounted to tailcan interior (right).

To connect the two electronic boxes in the tailcan to the telemetry system in the service module a cable was attached to the outer surface of the motor case. Two feedthroughs in motor adapter and tailcan were used for the cable routing.

Figure 7. FOS instrumentation of the motor case of Improved Orion second stage.

To protect the cable during flight it was covered with adhesive Aluminium tape and a thick layer of red high-temperature silicone as shown in Fig. 7.

To measure the temperature of the second stage motor case at different locations a fiber optic temperature measurement system (FOS) was integrated into the second experiment service module. Four optic fiber lines with six temperature measurement locations each were attached at the top and bottom location on the motor case (+/- 90° in circumferential direction compared to the cable routing shown in Fig. 7). For each location two fibers were routed in parallel for redundancy purposes. Two additional feedthroughs in the motor adapter were used to route the fibers to the electronic box in the service module. The fixation of the optic fibers to the motor housing was done using epoxy adhesive. Additionally all fiber lines were protected with adhesive Aluminium tape.

III. Instrumentation and Data Acquisition

A. Instrumentation

The ROTEX-T flight experiment was equipped with overall 96 sensors, 4 HD-cameras and 4 fiber optic lines (FOS) for temperature measurements. The following table presents an overview of used sensors and locations.

Table 1. ROTEX-T instrumentation overview

	Nose part	7°-cone	20°-flare	Experiment service module 1	Experiment service module 2	Second stage motor case	Second stage tailcan	Second stage fin
Absolute pressure sensor	-	9	5	3	-	-	-	-
PCB pressure sensor	-	6	-	2	-	-	-	-
Total heat flux sensor (HFM)	-	5	6	3	-	-	-	-
Coaxial-thermocouple	-	10	6	-	-	-	-	-
Structure-thermocouple	2	6	4	3	3	-	13	6
Full-bridge strain gauge	-	-	-	-	-	-	-	3
Strain gauge rosette 0°/45°/90°	-	-	-	-	-	-	-	1
FOS measurement locations	-	-	-	-	-	24	-	-
HD-cameras	-	-	-	-	4	-	-	-

For surface pressure measurements Kulite absolute pressure transducers of the type XTE-190M were used with a measurement range of 1.7 bar. For one pressure transducer (KU7) on the 20°-flare a higher measurement range of 3.5 bar was used. The sensors on the 7°-cone were mounted flush with the surface, as their maximum operating temperature of 273°C was well above the expected surface temperatures. As the calculated temperatures on the flare surface exceeded the maximum working temperature, all pressure sensors on the 20°-flare, except for transducer KU7, were mounted on thermally isolated structures and had a separate stainless steel pressure port mounted flush with the conical surface. The connection between pressure port and sensor was done by stainless steel tubing.

As the surface temperatures on experiment service module 1 were expected to remain below 200°C the three pressure sensors were integrated flush with the module surface. The absolute pressure sensors were sampled with different frequencies according to Fig. 8 - Fig. 11.

For the first time PCB high frequency pressure transducers were used during a hypersonic flight to measure the pressure fluctuations with a sampling rate of 2 MHz. Due to the high frequency sampling all PCB pressure sensors were integrated flush with the surface using high-temperature silicone glue.

Based on SHEFEX-I and SHEFEX-II heritage total heat flux measurements were carried out using heat flux microsensors (HFM 7E/H) of the Vatell company. These sensors have a maximum working temperature of 400°C (600°C for short duration) which is sufficient for the ROTEX-T flight, even for the locations on the 20°-flare. Coaxial-thermocouples of the Shock Wave Laboratory of the RWTH Aachen University were used for fast surface temperature measurements[6]. For the 7°-cone the coaxial-thermocouple sensors consisted of four individual coaxial-thermocouples in one sensor housing connected in series to increase the sensitivity. Due to the higher heat flux it was not necessary to use this design on the 20°-flare. In general these surface temperatures can be used to calculate the surface heat flux by assuming one-dimensional heat conduction and semi-infinite wall thickness. But the semi-infinite wall thickness assumption is only valid for a short time until the back end temperature of the sensor is increasing. Therefore the temperature at the back end of the coaxial-thermocouples was also measured by a separate thermocouple incorporated into the sensor design.

In addition to the temperature measurements on the vehicle surface, several standard type K thermocouples were attached to the interior structure of cone and flare to measure the inner temperature distribution. Further type K thermocouples were integrated into fin and tailcan of the second stage motor to measure the structure temperatures. The fin was also equipped with strain gauges to measure the deformation in different axes during ascent and re-entry. To measure the outer surface temperature of the second stage motor housing four optic fiber lines with six measurement locations each were attached to the housing using epoxy adhesive and Aluminium tape.

The following four figures show the sensor distribution on the surface of 7°-cone, 20°-flare and experiment service module 1. The figures also show the allocation of the sensors to the different data acquisition systems.

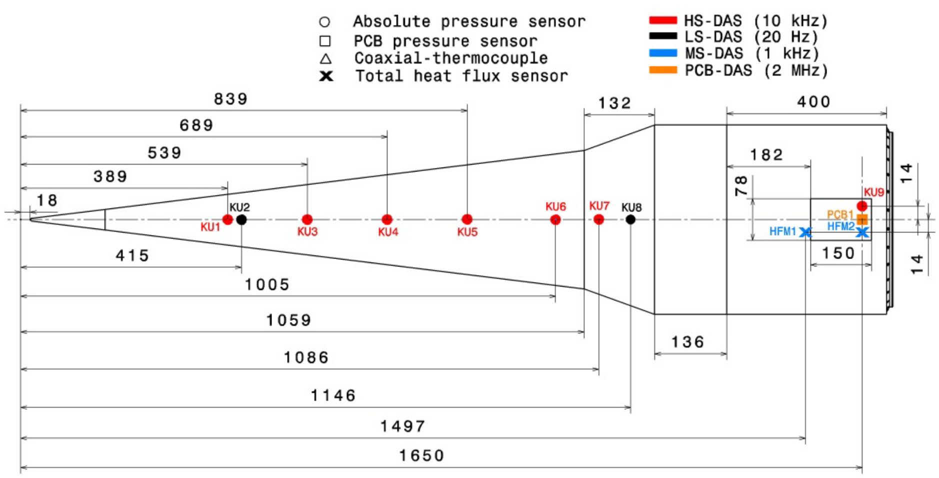

Figure 8. ROTEX-T payload sensors top line (0°).

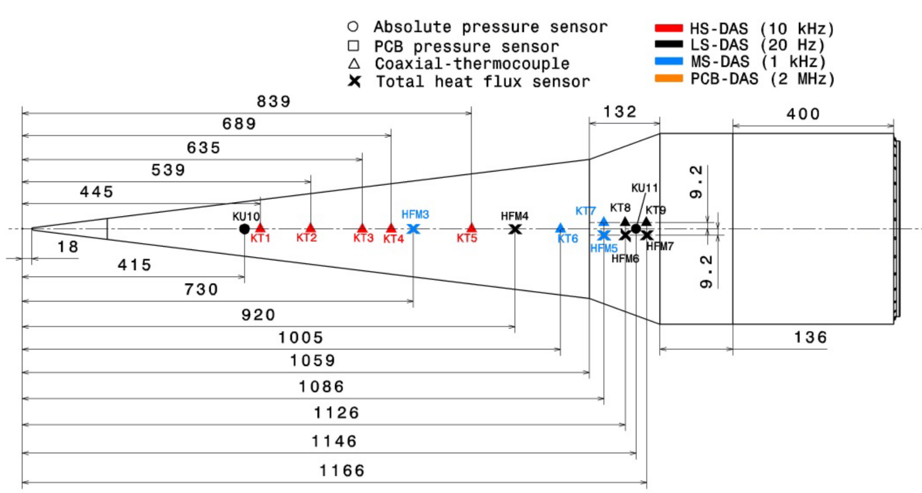

Figure 9. ROTEX-T payload sensors right line (90°)

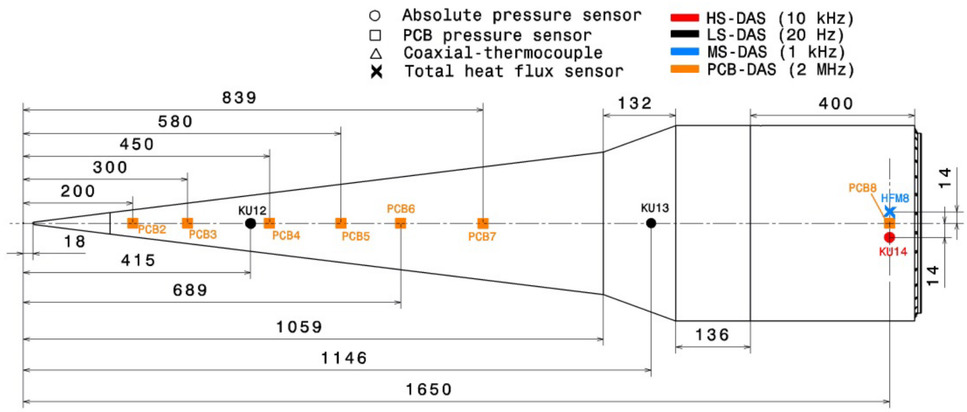

Figure 10. ROTEX-T payload sensors bottom line (180°).

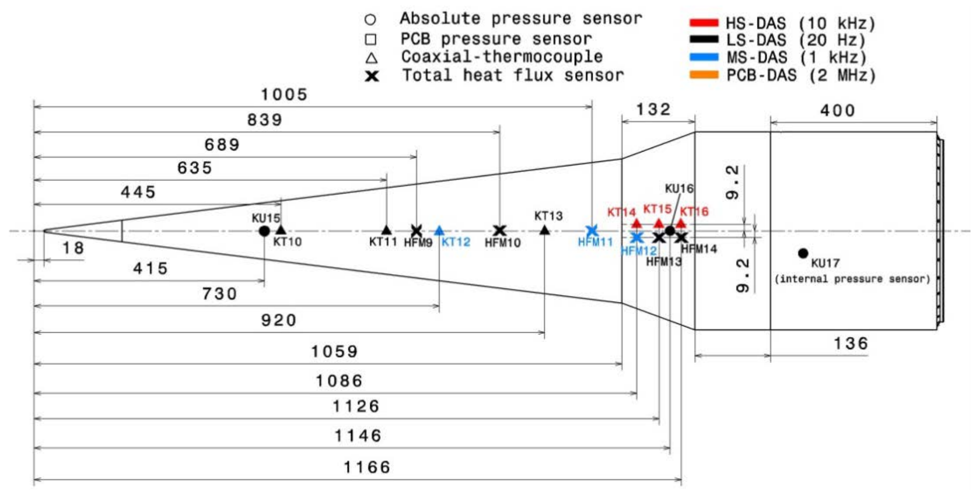

Figure 11. ROTEX-T payload sensors left line (270°)

The instrumentation layout of the second stage fin is presented in Fig. 12. Three full-bridge strain gauges were attached to the fin frame and one strain gauge rosette was fixed to the fin cover sheet. At each measurement location a thermocouple was installed near the strain gauges. Two further thermocouples were integrated into the fin leading edge.

The tailcan was instrumented with overall 13 type K thermocouples mounted to tailcan frames, tailcan cladding and electronic boxes. In Fig. 13 the thermocouple positions on tailcan frames and cladding are shown. Thermocouple TC1-TC5 were mounted to the inner surface of the tailcan cladding and TC6-TC9 were fixed to the inner side of the tailcan frames. All tailcan thermocouples had a ring lug for fixation using screws. The thermocouples TC10-TC13 were attached to the fixation screws of the two electronic boxes mounted inside the tailcan (see Fig. 6).

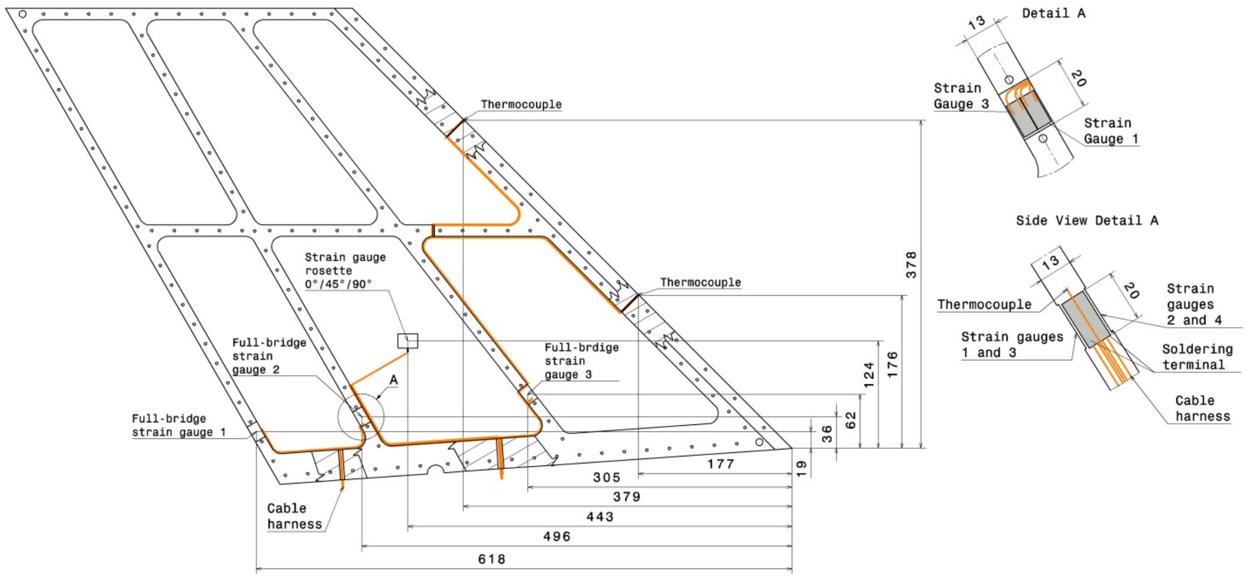

Figure 12. ROTEX-T fin instrumentation layout

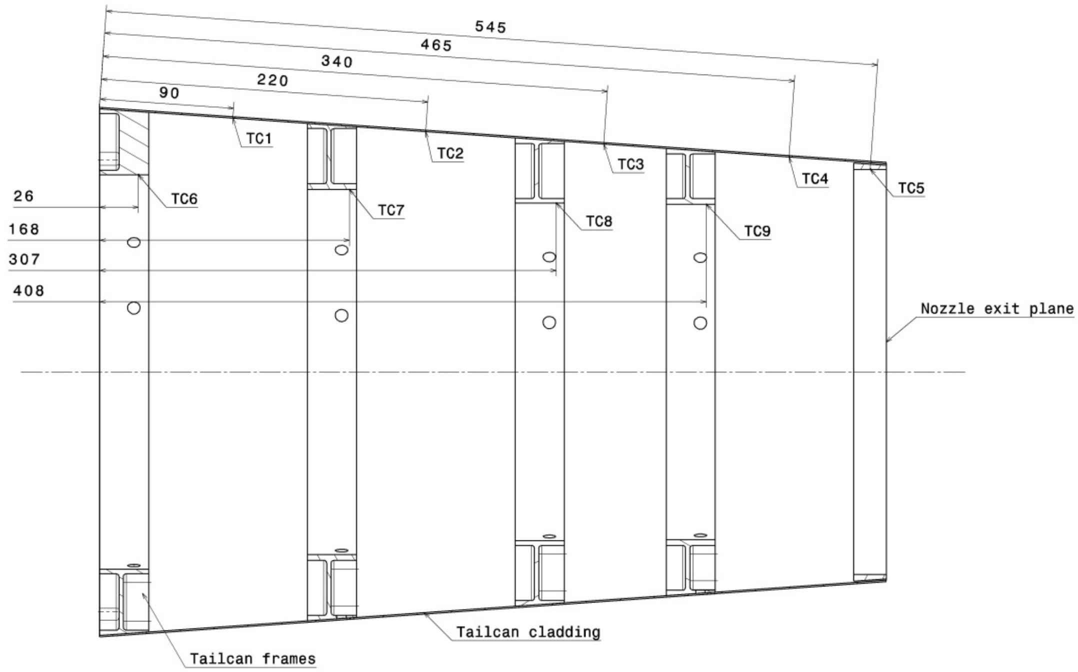

Figure 13. ROTEX-T tailcan thermocouple instrumentation layout

B. Data Acquisition Systems

Overall four different data acquisition systems were used for the ROTEX-T flight experiment, which are described in this section. The sensor signals were partially transmitted to the ground station via telemetry, but due to the high amount of sensors and the sampling frequencies of the high-speed systems most data were stored on-board. Because ROTEX-T did not have a parachute system, the necessary memory units were designed to survive the impact with high velocity.

Low-speed data acquisition system

The low-speed data acquisition system was already used for the SHEFEX-I, SHEFEX-II and EXPERT flight experiments and was therefore flight qualified. It consists of seven circuit boards in 160x100 mm format integrated into an aluminium box. Three analogue amplification boards are used for sensor signal conditioning (amplification, filtering). Each analogue amplification board can process 28 sensor signals and each input channel can be configured to measure millivolt, Ohm or milliampere. These boards were designed and manufactured at DLR in Cologne. The analogue to digital conversion is performed by three multifunction cards provided by DLR MORABA which are used in a master/slave configuration. The master-board is responsible for sending the digitized sensor data to the telemetry transmitter via a serial communication line. A separate power distribution board is providing the necessary voltages for the active sensors like the pressure transducers. The box is powered with a nominal voltage of 28 Volt. To convert this voltage to the needed voltages for the electronic boards, several DC/DC converters are used which are attached to the side wall of the box.

The sensor signal sampling frequency of the low-speed data acquisition system is configurable. For the ROTEX-T flight experiment the sampling frequency was set to 20 Hz. In Fig. 14 the design of the low-speed electronic box is shown. For ROTEX-T the box size was 214 x 172 x 121 mm (L x W x H) with a weight of approximately 4.5 kg.

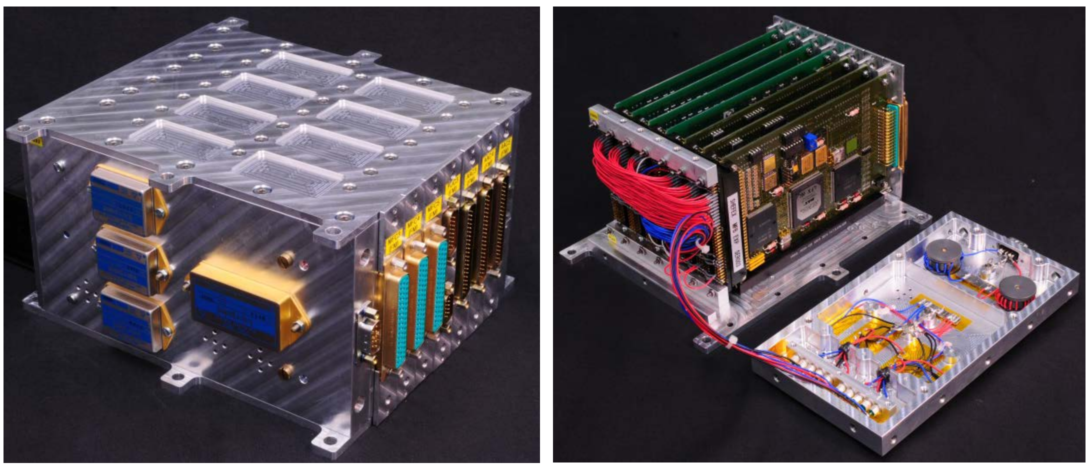

Figure 14. Low-speed data acquisition electronic box design.

Medium-speed data acquisition system

The medium-speed data acquisition system was developed and manufactured by the Supersonic and Hypersonic Technologies Department of the German Aerospace Center. It consists of several circuit boards with a size of 100 x 80 mm integrated into aluminium frames which is shown in Fig. 15. Each board is equipped with a D-sub 37 connector and can process 18 sensor signals with a sampling frequency of 1 kHz. Each input channel can be configured to measure millivolt, Ohm or milliampere. Nine of the 18 channels can also be configured to supply active sensors. Several circuit boards can be stacked to process the necessary number of sensors using a master/slave configuration. The master-board is used for the communication via a RS485 line. The electrical connection between the different boards is done via back-end connectors. Figure 15 shows a medium-speed electronic box with two acquisition boards (lower two boards). The upper frame does not contain a circuit board and is reserved for internal cabling to the DC/DC-converters on the top plate. The second frame from the top houses the circuit board used for HD-camera control which was not integrated at the time the picture was taken. The box size for the medium-speed data acquisition system located in experiment service module 2 with four frames was 138 x 123 x 88 mm (L x W x H) with a weight of 1.2 kg. For the two boxes in the tailcan shown in Fig. 6 one acquisition board and one empty frame for internal harness was used for each box.

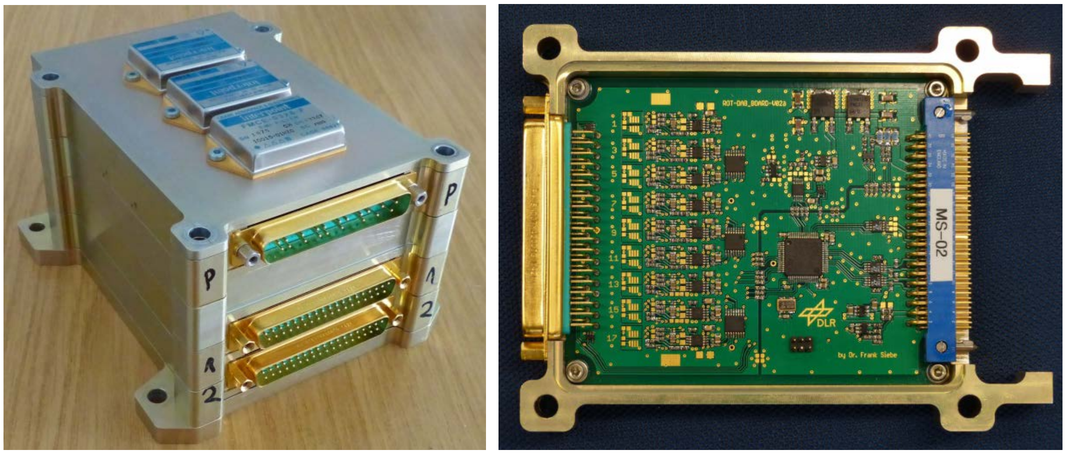

Figure 15. Medium-speed data acquisition system.

Because of the sampling frequency of 1 kHz and the limited bandwidth of the telemetry transmitter, most sensor data from the medium-speed system were stored on-board in a separate memory unit shown in Fig. 16. This memory unit was developed by the same department and consists of a small circuit board integrated into a steel housing that is able to survive the impact with high velocity. The circuit board contains an industrial SD-card for data storage. An attached D-sub 25 connector is used for communication. The size of the memory unit was 83 x 102 x 48 mm (L x W x H) with a weight of 1.6 kg.

Figure 16. Medium-speed data acquisition system memory unit.

High-speed data acquisition system

The high-speed data acquisition system was a new development in cooperation with an external company. It is able to sample eight PCB pressure sensors at a frequency of 2 MHz and eight absolute pressure sensors and eight coaxial-thermocouples at a sampling rate of 10 kHz. Because of the high sampling rate most of the sensor data were stored in the internal memory, only a small amount was transmitted via telemetry. The electronic boards of the high-speed data acquisition system are based on multiple FPGAs, microcontrollers and a low level flash memory. The boards and the memory are integrated into a steel cylinder with a wall thickness of 12 mm. The remaining space inside the cylinder is filled with a potting compound. A further aluminium cylinder is used as outer housing with a wall thickness of 7.5 mm. Between steel and aluminium cylinder a rigid foam is used for damping the shock loads during impact. The sensor signal conditioning and analogue to digital conversion are performed by several separate small front-end electronic boxes that are mounted close to the sensors. For the PCB pressure sensors overall four front-end electronic boxes are used, each containing two circuit boards (one for each sensor). Two further boxes with a different layout are used for the eight coaxial-thermocouples and eight absolute pressure transducers. The complete data acquisition system is shown in Fig. 17. The main unit containing the memory is shown on the left image, the front-end electronic box for the PCB pressure sensors is presented on the upper right image and the box for the other sensors on the lower right image. The diameter of the main cylindrical unit was 160 mm with a height of 254 mm and weight of approximately 12 kg. The size of the PCB pressure sensor front-end electronic box was 86 x 49 x 32 mm (L x W x H) and the size of the other front-end electronic box was 109 x 70 x 18 mm.

Figure 17. High-speed data acquisition system main unit (left) and front-end electronic boxes (right).

Fiber optic data acquisition system

The electronic box for the fiber optic data acquisition system is shown in Fig. 18 mounted to the fixation frame on the bulkhead of the second experiment service module. The fiber optic measurement system was contributed by an external partner. The small blue box also mounted to the fixation frame contains the crash-resistant memory stick on which most of the sensor data were stored. In addition to the memory stick, a conventional SD-card is integrated in the electronic box. The electronic box is able to process four optic fibers. The number of possible temperature measurement locations per fiber depends on the selected measurement range. For ROTEX-T six measurement locations for each fiber were used with a measurement range up to 1000°C. Having a weight of approximately 1.3 kg, the size of the electronic box was 174 x 160 x 65 (L x W x H).

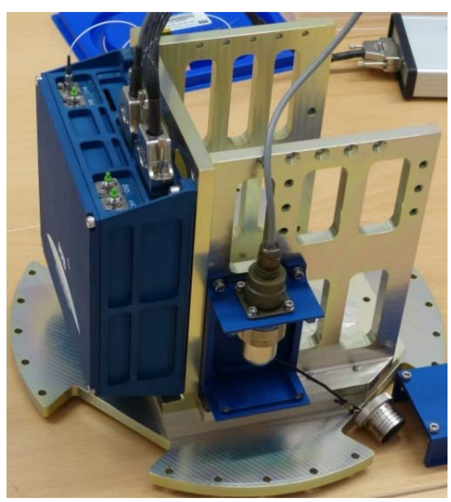

Figure 18. Fiber optic data acquisition system and memory box attached to mounting frame and bulkhead.

To transmit the sensor data to the ground station three telemetry channels were available. Two channels had a baud rate of 56700 baud and one channel had a baud rate of 38400 baud. The data stream concept for the telemetry is shown in Fig. 19. One 56700 baud channel was used to transmit part of the high-speed system data. The data of the medium-speed system (including the sensors in fin and tailcan) were partially transmitted using the 38400 baud channel. The sensor signals of all sensors attached to the low-speed acquisition system were completely transmitted via the second 56700 baud channel. Because the baud rate was not completely utilized by the low-speed system, a part of the fiber optic system data was also incorporated into the same data stream. In addition to the telemetry an umbilical (cable connection) was used for a two-way communication to the payload before lift-off. The telemetry only had a downlink, so it was not possible to send commands to the vehicle during flight.

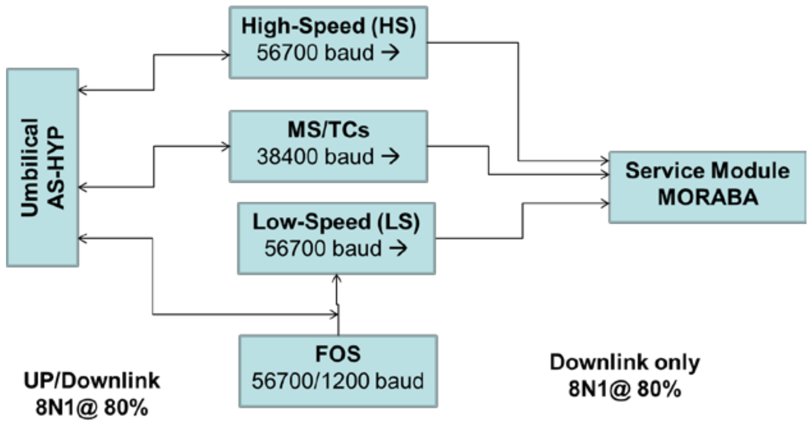

Figure 19. ROTEX-T data stream concept.

IV. Flight Data

A. Flight Trajectory

As shown in Fig. 20 the first rocket stage accelerated the entire system with a total weight of 1485 kg to a speed of 768 m/s. After burn-out of the first motor and its separation a short phase without thrust in an altitude range between 2.5 km and 8.5 km followed. At a flight time point of about 14s the second stage motor was ignited and provided a thrust for about 25 seconds. In the ascent phase the vehicle reached a maximum velocity of 1654 m/s at an altitude of 39 km. After reaching an apogee of 183 km, the descent flight was carried out only aerodynamically without any RCS support. The second stage motor remained attached during re-entry. The re-entry configuration is shown in Fig. 2. The flight angle of attack during ascent was kept below about 1.5° which is confirmed by the measured pressure data from four pressure ports on the 7°-cone (see Fig. 23). Measured heat fluxes show an excellent correlation to the pressure data. In addition to the instrumentation of the double cone on top of the flight configuration, one fin of the second stage was also instrumented with strain gauges and thermocouples. The deformation of the fin, in particular in lower altitudes, was measured successfully.

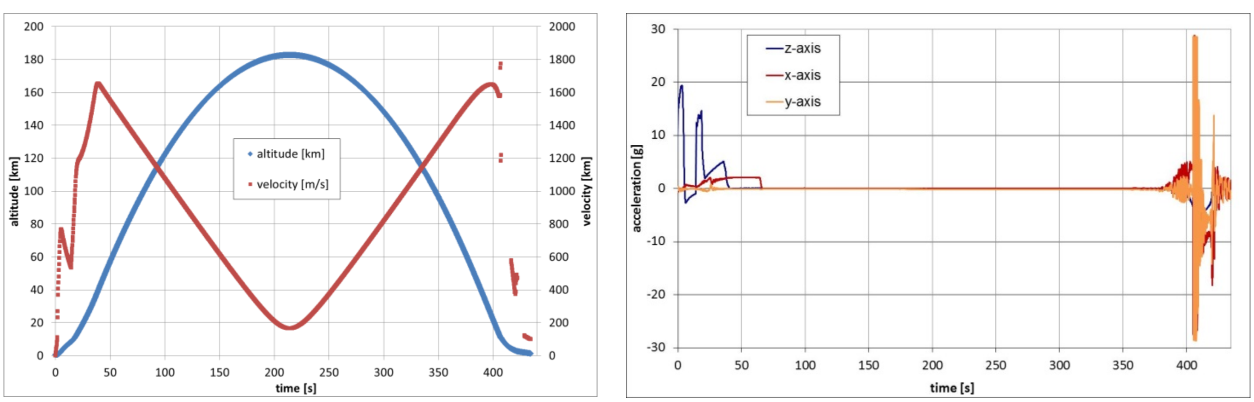

Figure 20. Flight altitude, velocity and accelerations of ROTEX-T flight experiment.

After a hot descent flight the payload separated from the second stage at an altitude between 10-15 km and afterwards decelerated by tumbling. It finally impacted in an uninhabited part of northern Sweden with a speed below 98 m/s which was the last recorded velocity before loss of telemetry. The memory units of high-speed, medium-speed and fiber optic data acquisition system were designed for a high impact velocity of the payload and 'survived' the hard landing. After separation from the second stage the telemetry system was still working. Due to the strong tumbling directly after separation some communication losses occur, but sensor data were received down to an altitude of 1.2 km.

On the right side of Fig. 20 the accelerations for the x, y and z-axes are shown. The z-axis corresponds to the vehicle axis and the values therefore represent the accelerations caused by the rocket motors with a maximum of 19.4 g during the first stage burn-phase. The y- and x-axes are perpendicular to the z-axis building a right hand system. Figure 21 shows the accelerations during ascent and descent in more detail. The z-axis acceleration becomes zero at about 40 seconds which corresponds to the burn-out of the second stage. The x-axis accelerometer is placed at some distance to the vehicle axis. Due to the spin stabilization this accelerometer measures a centrifugal acceleration which remains constant after second stage burn-out. At 65 seconds after lift-off the Yo-Yo system is activated reducing the roll rate and the x-axis acceleration to zero. The y-axis accelerometer is placed very close to the vehicle axis and therefore only measures a very small centrifugal acceleration.

During descent the z-axis accelerometer shows the aerodynamic deceleration. The oscillatory behaviour of x- and y-axis accelerometers indicates a tumbling motion of the vehicle. At a flight time of 405 seconds the payload was separated from the Improved Orion motor, which created very high accelerations on the x- and y-axis.

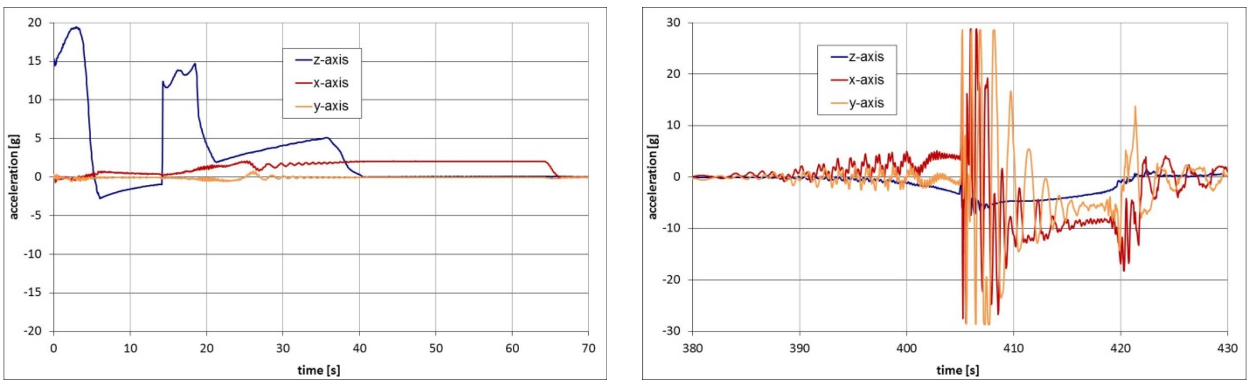

Figure 21. Accelerations during ascent (left) and descent (right).

B. Measured pressure and heat flux

Fig. 22 shows a detailed view of flight velocity and altitude for the first 30 seconds of flight. After that time the vehicle velocity is 1370 m/s at an altitude of approximately 25 km. The corresponding Mach number, which is calculated using the CIRA86 atmospheric model, is about 4.5 (Fig. 22, right). The unit Reynolds number at the same time point is 3.5 million.

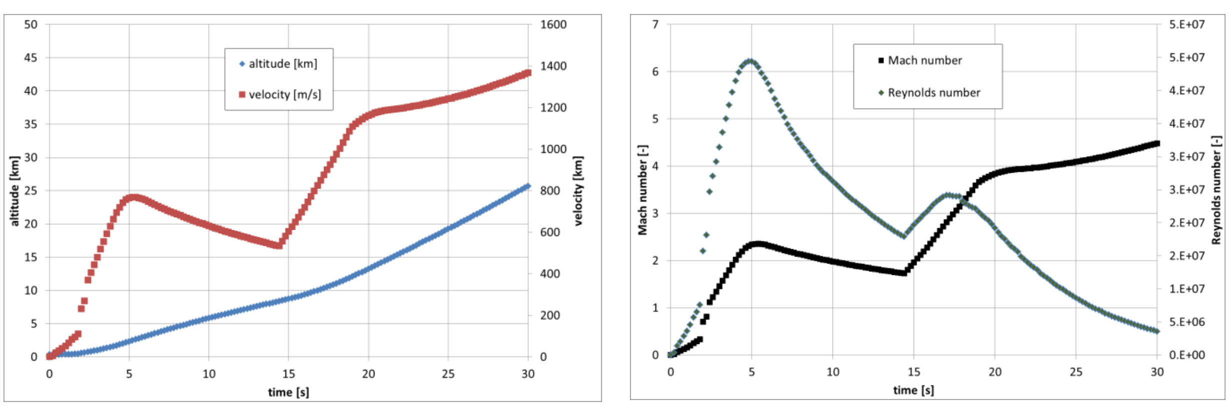

Figure 22. ROTEX-T flight parameters during ascent.

The maximum Reynolds number of 44 million is reached after the boost phase of the first stage motor at t=5s. A second peak in the unit Reynolds number with a value of 24 million occurs after the ignition of the second stage motor. The corresponding Mach number at that time point is 2.8.

The surface pressure distribution on 7°-cone and 20°-flare was measured using absolute pressure transducers. As shown in Fig. 8 – Fig. 11 the pressure ports 2, 10, 12 and 15 are placed on the cone at the same axial distance from the nose tip every 90° in circumferential direction. Pressure ports 8, 11, 13 and 16 are placed on the flare in the same manner. A slight pressure increase by passing the sonic speed is measured by all four transducers on the cone (Fig. 23, left) at an altitude of 700 m. At 25 km altitude the measured pressure at the ports 2, 10, 12 and 15 is between 32-48 mbar. Due to the angle of 20° the measured pressure on the flare is significantly higher (Fig. 23, right).

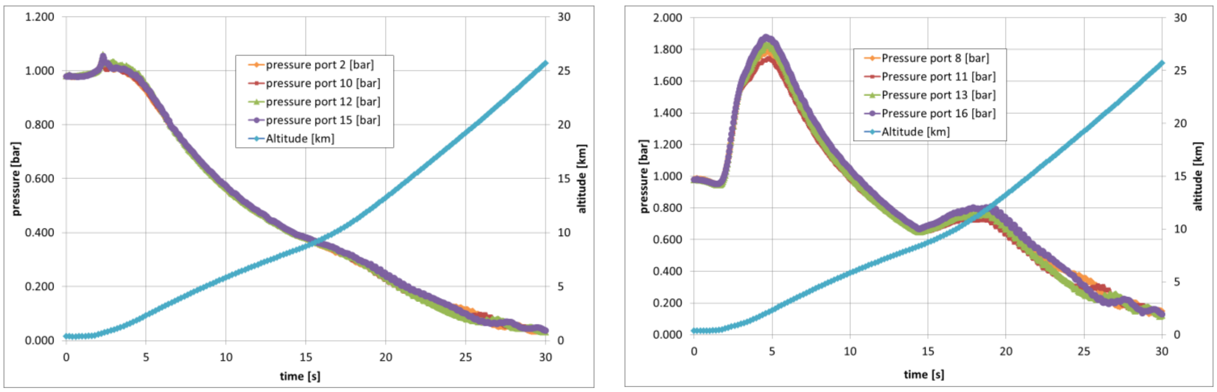

Figure 23. Measured pressures on cone and flare during ascent of ROTEX-T.

As shown in Fig. 24 on the cone in subsonic flight regime all sensors show very good agreement. After passing the sonic speed some oscillations, in particular on the cone pressure data, are visible. On the flare the differences between the measured pressures are higher. The highest pressure occurs at pressure port 16 over the complete shown time interval (0-10s). The situation on the cone is different with the pressure maximum between 0 and 6 seconds occurring at pressure port 12, which is not on the same instrumentation line than pressure port 16.

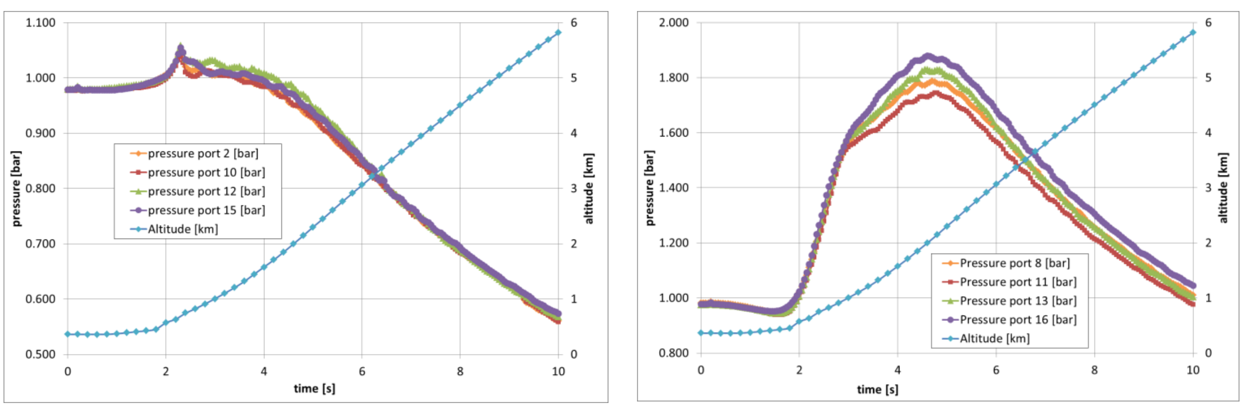

Figure 24. Detailed view of measured pressures on cone and flare during ascent of ROTEX-T.

The results on the cone indicate a small angle of attack. The differences in the pressure data on the flare require a more detailed analysis of the flow field like the impact of imperfect flow separation and reattachment.

As mentioned before ROTEX-T was a low cost flight experiment without inertial measurement unit and reaction control system. Therefore no attitude control was carried out and the aerodynamic and gravitational forces defined the vehicle trajectory. During descent the vehicle was decelerated by aerodynamic forces, which led to tumbling motions during most of the descent phase. Measured pressure data on cone and flare reflect this motion clearly (Fig. 25). The almost constant phase shift between ports 2 and 12 and ports 10 and 15 in the time period from 390 seconds to 402 seconds supports this explanation. The data of the flare pressure ports 8,13 and 11,16 show exactly the same behaviour.

Shortly before payload separation, which takes place at about 405 seconds, the payload is oriented by increasing aerodynamic forces on the second stage fins which reduces the tumbling and the corresponding pressure fluctuations. At the same time the boundary layer transition from laminar to turbulent flow occurs on the cone which can be seen in Fig. 26. The heat flux sensor HFM4, which is located 920 mm from the nose on the same instrumentation line as pressure sensor 10, shows the begin of the transition at 401 seconds. The heat flux sensors HFM9 and HFM10 are placed on the instrumentation line of pressure sensor 15 at 689 mm and 839 mm from the nose tip, respectively. HFM10 measures the transition more or less at the same time as the sensor HFM4. The sensor HFM9, which is located upstream of HFM10, indicates a later transition around 403 seconds with a stronger heat flux increase. The unit Reynolds number at this point is approx. 15 million, while the transition Reynolds number for HFM4 and HFM10 is around 10 to 12 million. The Mach number between 400 and 403 seconds is nearly constant with a value of about 5.4. At a flight time of 405 seconds the payload is separated from the second stage motor.

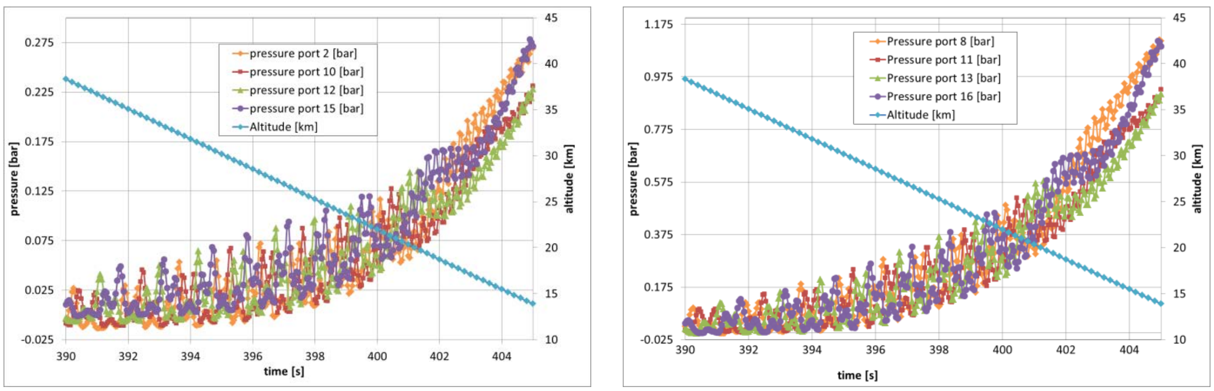

Figure 25. Measured pressures during last phase of ROTEX-T descent.

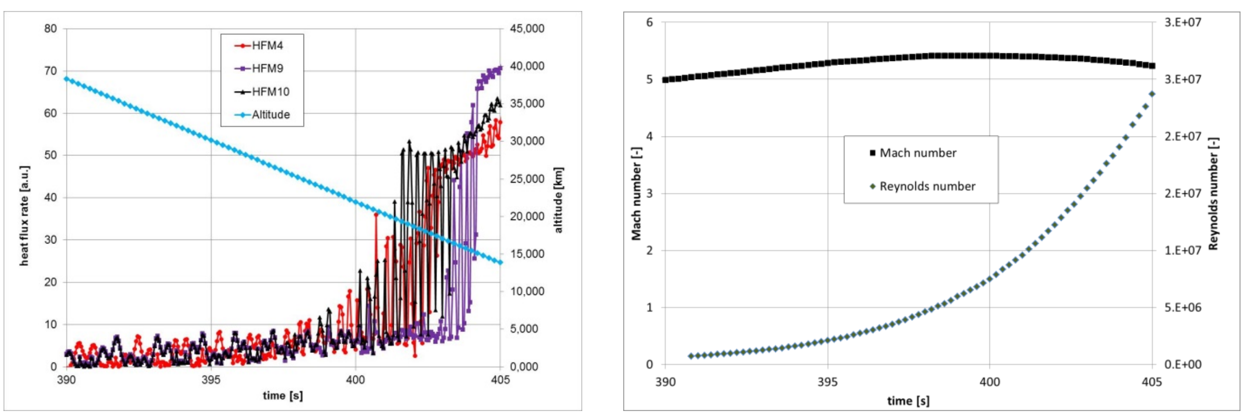

Figure 26. Measured heat flux, Mach number and Reynolds number during ROTEX-T descent phase.

V. Conclusions

ROTEX-T (Rocket Technology Experiment-Transition) was successfully launched on 19 July 2016 at 06:05 am CEST from the Esrange Space Center near Kiruna in northern Sweden. The flight experiment was supported by students of the RWTH Aachen University by means of analysis and numerical simulations of selected items. Although ROTEX-T was carried out as a low cost flight experiment without Inertial Measurement Unit (IMU), Reaction Control System (RCS) and parachute system, the following important achievements were made:

- The launch, boost, stage separation, Yo-Yo de-spin and payload separation were carried out without any anomaly.
- Because of missing attitude control the descent trajectory was only defined by aerodynamic and gravitational forces which led to a tumbling motion of the vehicle. The tumbling was damped around the end of the descent phase due to increasing aerodynamic forces on the second stage fins.
- Because of the missing parachute system the payload was separated from the second stage at around 15 km altitude and could be recovered after impact.
- Even without costly IMU, RCS and parachute a successful recovery was achieved. Figure 27 shows the payload after its impact with high velocity (left) and all three recovered data acquisition units after payload disassembly (right).
- All three data acquisition systems with sampling frequency ranges of 20 Hz, 1 kHz, 10 kHz and 2 MHz worked perfect. The on-board memory units also worked well and all flight data were recovered.
- Most of the ROTEX-T instrumentation provided very useful data.
- ROTEX-T provided data on aerothermal heating during ascent and descent, which will be analyzed and published in the coming months.

Figure 27. ROTEX-T payload and data acquisition systems after landing without parachute.

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