IAC-09-A2.5.7

MAPHEUS - THE MAIDEN FLIGHT OF A NEW VEHICLE FOR MICROGRAVITY EXPERIMENTS

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ABSTRACT

There are numerous materials science experiments in microgravity, which can be realized on sounding rockets, e.g. the gelation of aerogels, directional solidification of alloys and diffusion measurements in metallic melts. Such a rocket must offer a period of good microgravity-conditions for more than 120 s. The MAPHEUS (Materialphysikalische Experimente unter Schwerelosigkeit) rocket of the German Aerospace Center DLR meets these requirements.

The payload is based on modules with 356 mm diameter, which are also used in the REXUS project. MAPHEUS implements the newly developed REXUS service-system. This service-system can control the power supply and handles data communication and time event management of the scientific experiments. An RCS-Module (Rate-Control-System) has been designed and built. This module contains a tank filled with pressurized gas (nitrogen), solenoid valves and nozzles, which are used to reduce the spin during the ballistic flight phase to less than 30°/min providing excellent microgravity conditions. During the maiden flight, in May 2009 at Esrange, Sweden, the payload was transported with a double stage solid propellant rocket up to an apogee of about 140 km. The first stage, a Nike motor, burned for 3.5 s and then, 9 s after lift-off, the second stage, an Improved Orion motor, ignited. At an altitude of about 70 km a yo-yo system decreased the rotation of the vehicle about its' longitudinal axis, which was spin-stabilized during the ascent. After the second stage was separated and the rotation rates were reduced by the RCS, the experiment phase began at an altitude above 100 km.

The scientific payload of MAPHEUS-1 consisted of three DLR internal experiment modules and a battery module from the DLR Institute of Materials Physics in Space, a measurement platform from the University of Applied Science Aachen, and the RB-MUSC from DLR Köln. The three material science experiments launched were AEROGET, an experiment to create frequency doubling aerogels, ATLAS-M, an experiment for diffusion measurements in molten metals and ARTEX-M, an experiment for directional solidification of AlSi-alloys. After the experiment phase, the payload re-enters the atmosphere and was decelerated by the aerodynamic drag. At an altitude of about 4.6 km the parachute system was released and the payload thus decelerated to a terminal velocity of 8 m/s. The DLR Institute of Space System was responsible for the project management and the DLR Mobile Rocket Base provided the rocket hardware and conducted the operations during campaign.

This paper gives an overview of the MAPHEUS-1 vehicle, the experiments, the successful maiden flight of the rate-control-system and the campaign. It also includes flight results and gives an outlook on the MAPHEUS programme.

1. INTRODUCTION

The development of MAPHEUS-1 started with the Kick-Off Meeting in June 2008, held by DLR in Cologne.

Milestones	Date
Kick-Off Meeting at DLR Cologne	2008-06-18
Status Meeting at DLR Oberpfaffenhofen	2008-09-17
BATT-M Vibration Test	2008-11-18
Bench Test of Exp. Flight Hardware at DLR Oberpfaffenhofen	2009-01-19
Experiment Vibration Tests at University of Armed Forces in Neubiberg	2009-02-19
Flight Sim. Test at DLR Oberpfaffenhofen	2009-04-22
Recovery System Bending Test at University of Armed Forces in Neubiberg	2009-04-24
Environmental Tests at Astrium in Ottobrunn	2009-04-27
Transport of PL to Esrange	2009-05-04
Beginning of Campaign at Esrange	2009-05-11
Practise Countdown	2009-05-20
Launch of MAPHEUS-1	2009-05-22

Table 1: The MAPHEUS Schedule [10]

The challenging project plan required tremendous effort of all participating partners. First of all, the experiments had to be designed and built, starting from the experiment concept at DLR Institute of Material Physics in Space. Second driver was the development of the Rate-Control-System (RCS) at the DLR Mobile Rocket Base. The third important constraint on the time schedule was given by the REXUS programme with annual launches in March. MAPHEUS-1 used several components from REXUS-5, especially the REXUS service system and therefore a time gap of at least 2 months was necessary between the REXUS and the MAPHEUS campaigns.

On the 22nd of May 2009 DLR launched successfully the MAPHEUS-1 rocket from Esrange in Northern Sweden. Only eleven months after the kick-off meeting. Table 1 shows the critical time frame in overview.
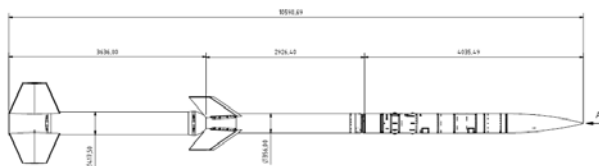

Figure 1: MAPHEUS-1 two-stage unguided solid propellant sounding rocket [8]

2. THE VEHICLE DESIGN

MAPHEUS-1 was a two-stage unguided solid propellant sounding rocket similar to REXUS-4 [9]. The vehicle consisted of a Nike motor as 1st stage, an Improved Orion as 2nd stage, a motor adapter, a recovery system, a rate-control-system, a service system, the IGAS module, five experiment modules, a nosecone adapter and a nosecone. The payload is based on modules with 356 mm diameter, which are also used in the REXUS project.

Figure 2: The MAPHEUS Rocket on the Launcher

2.1. Lift-Off Configuration

The total lift-off mass of MAPHEUS-1 was 1221 kg with the motor mass contributing more than 1000 kg. Including both motors, the MAPHEUS-1 rocket had a length of 10.6 m. The payload mass was 198 kg including a scientific payload mass of 113 kg. The polar moment of inertia of the payload was measured to be 3.39 kgm².

Two requirements on the payload configuration are important to ensure a safe flight of a sounding rocket. The first requirement is the centre of gravity during lift-off that has to be ahead of the centre of pressure.

The centre of gravity for the lift-off configuration referenced to the aft plane of the motor adapter was measured at 1564 mm, 36.2 % of the payload length [8].

2.2. Re-entry Configuration

For the re-entry a center of gravity close to 50 % of the payload length is necessary to avoid a stable attitude of

the vehicle during the descent and prevent the recovery system from too much heating. There was no scientific requirement to eject the nosecone but analysis of the re-entry configuration made it necessary to take this decision to ensure a safe re-entry.

The centre of gravity for the re-entry configuration was measured at 1258 mm (49.7 %) measured from the separation plane between motor adapter and recovery system. The re-entry payload mass was 172 kg.

1st Stage:	598.5 kg
2nd Stage	424.5 kg
Payload	197.7 kg
Motor Adapter + Manacle Ring	12.7 kg
Recovery System	23.0 kg
RCS Module	11.0 kg
IGAS Module	10.0 kg
Service System	19.2 kg
ARTEX-M Module	20.5 kg
Battery Module	26.0 kg
ATLAS-M Module	29.5 kg
RAMS Module	12.5 kg
AEROGET Module	14.6 kg
Nosecone Adapter	5.1 kg
Nosecone + Manacle Ring	12.9 kg
Total	1220.7 kg

Table 2: The MAPHEUS-1 Mass Budget [8]

2.3. Frequency List

The MAPHEUS-1 payload has been equipped with several transmitters. Following tables show frequency lists of the service module, the IGAS module and the recovery system.

Denotation	Transfer Rate	Power (W)	Frequency (MHz)
TM TX	500 kbit/sec.	5	2292.5
TV 6 TX	8 MHz (BAS/Pal)	10	2338.1
TC RX	19.2 kBit/sec	Passive	449.95
GPS RX	BW= 2 MHz	Passive	1575.4

Table 3: The Service System Frequency List [8]

Denotation	Transfer Rate	Power (W)	Frequency (MHz)
GPS RX)	BW = 2 MHz	Passive	1575.4

Table 4: The IGAS Experiment Frequency List [8]

Denotation	Transfer Rate	Power (W)	Frequency (MHz)
Beacon 1 (Tip)	1 KHz (AM)	0.2	244.05
Beacon 2 (Payl.)	1 KHz (AM)	0.2	240.80

Table 5: The Recovery System Frequency List [8]

3. DEVELOPMENT OF RCS SYSTEM

MAPHEUS implements the newly developed REXUS service system. This service system can control the power supply and as well as handling data communication and time event management of the scientific experiments. An RCS-Module (Rate-Control-System, see Figure 3) has been designed and built. This module contains a tank filled with pressurized gas (nitrogen), solenoid valves and nozzles, which are used to reduce the residual spin rate after yo-yo de-spin during the ballistic flight phase to less than 30 °/min providing excellent microgravity conditions. More information can be found in [1].
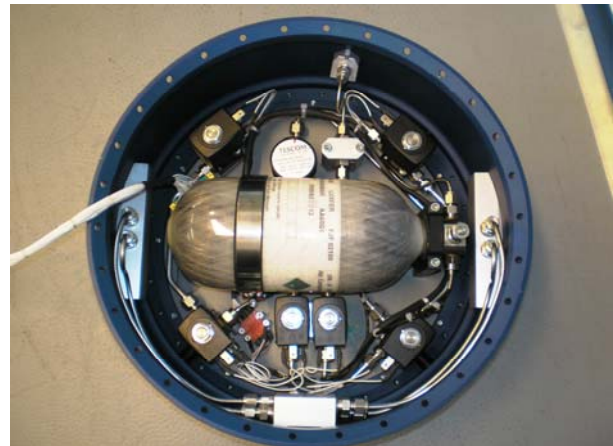

Figure 3: Top View of the RCS Module [1]

4. EXPERIMENTS

The scientific payload of MAPHEUS-1 consists of three experiment modules and a battery module developed and built by the DLR Institute of Materials Physics in Space. Additionally on board is a measurement platform from the University of Applied Science Aachen and the RB-MUSC of the DLR in Cologne. The three material science experiments are AEROGET (**Aero**gel **Gel**at**i**on), an experiment to process frequency doubling aerogels, ATLAS-M (**A**tomic **T**ransport in **L**iquid **A**lloys and **S**emiconductors), an experiment for diffusion measurements in molten metals and ARTEX-M (**A**luminum **R**esearch and **T**echnology **Ex**periments), an experiment for directional solidification of Al-based alloys. The measurement platform contains the RAMS (**R**esidual **A**ccelerations **M**easurement **S**ystem) experiment.

The letter 'M' abbreviates MAPHEUS (**Ma**terial**ph**ysikalische **E**xperimente **u**nter **S**chwerelosigkeit).

Additionally the IGAS module of the DLR Mobile Rocket Base has been implemented to the MAPHEUS-1 payload. IGAS has both an intelligent antenna and a standard antenna system with the appropriate GPS receivers.
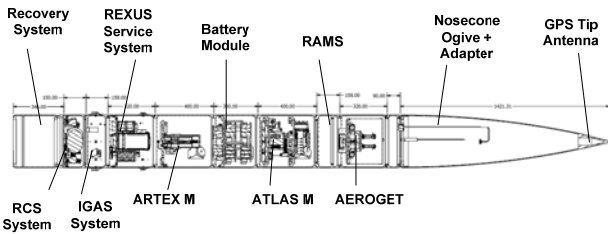

Figure 4: Sketch of the MAPHEUS-1 Payload [8]

4.1. ARTEX-M

One of the most challenging problems associated with casting in general is the influence of convection during all stages of solidification. The strength of fluid flow changes the as-cast internal microstructure such that the yield, fracture and fatigue strengths of the cast ingot can vary considerably. Although the importance of fluid flow has been recognized for decades, not even a simple model has been developed to predict the effect on microstructure.
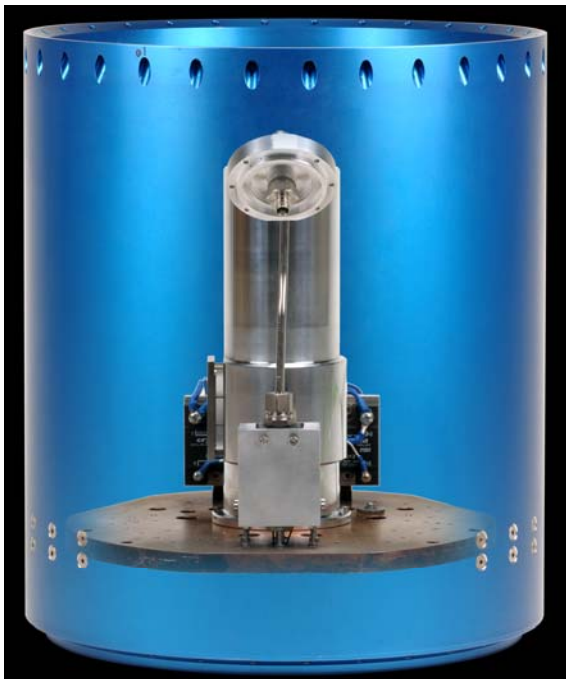

Figure 5: ARTEX-M Module [7]

The ARTEX-M experiment is part of the ESA-MAP project MICAST aiming to control experimentally fluid-flow patterns that affect microstructure evolution during casting, and to develop models for flow effect on as-cast structures. A microgravity environment is the chance to reduce all gravity-induced convections. Since AlSi-base alloys are the most important casting alloys in all light metal cast shops, the experiment investigates the microstructure evolution in AlSi6 alloys. Predecessors of the ARTEX-M experiment were flown on TEXUS and MAXUS. The ARTEX-M experiment closes a gap in experimental parameters left by these.

4.2. BATT-M

This module is equipped with rechargeable batteries of the LiFe-PO$_4$-type that supply energy for both the diffusion (ATLAS-M) and solidification (ARTEX-M) experiment. In six battery packs a total capacity of 27.6 Ah is provided with power redundancy for each of the experiments. Solid state relays are used to switch power. Temperature control of the experiments is done by pulse width modulation. A FPGA controller onboard managed communications, the I/O devices, data storage and process controlling.
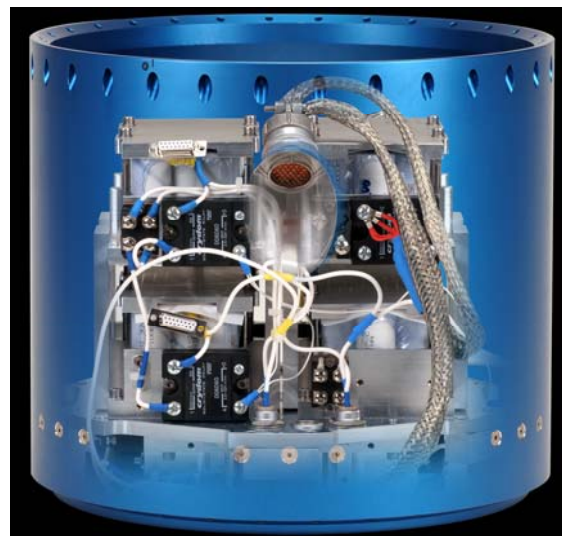

Figure 6: BATT-M Module [4]

4.3. ATLAS-M

In the laboratory, the measurement of thermophysical data of the melt, in particular of the chemical diffusion or interdiffusion coefficient, has a limited accuracy due to buoyancy-driven natural convection. Therefore microgravity benchmark experiments without disturbing effects are necessary in order to calibrate ground-based measurements.

In eight furnaces, sixteen samples were processed. In eight samples impurity diffusion of different elements in liquid Germanium was measured at 950 °C. In another

eight samples interdiffusion in Al-Cu and Al-Ni was measured at 700 °C.

Figure 7: ATLAS-M Module [3]

4.4. RAMS

During the sub-orbital rocket flight, different levels of accelerations are present. High vibration levels occur during launch and re-entry and reduced accelerations in the ballistic suborbital flight phase are expected. Depending on flight path several minutes of reduced gravity acceleration can be used for scientific experiments that require micro-gravity. In order to verify the quality of the reduced gravity environment and thus the actual residual acceleration during this phase, a measurement package, RAMS, of the University of Applied Science Aachen and the RB-MUSC of the DLR in Cologne was integrated in the MAPHEUS-1 payload consisting of high acceleration sensors, seismic acceleration sensors and a high resolution rate sensor for the rotation. The measured data can be compared with the on-board data measured in the service system and can be used as reference environmental data for the results of the material physics experiments. The data acquisition is based on a stand alone FPGA data acquisition system (DAQ) which is used for collecting and storing all data autonomously during flight with a high sampling rate on an on-board memory unit. A low data rate stream is transmitted over the rocket telemetry line to the ground station to monitor the actual state of DAQ and acceleration. Post-processing will give a set of precision environmental data for this flight. First application and verification on a sub-orbital rocket flight was on MAPHEUS-1.

4.5. AEROGET

The transformation of infrared light into visible needs materials with non-linear optical properties. Ferroelectric crystals like Bariumtitanate or Lithiumniobate allow the transformation of high intensity infrared laser light into, for instance, green (such as a laser pointer). Typically single crystals are used for such purposes, which are difficult to prepare and expensive. An alternative route utilizes small ferroelectric particles embedded into an aerogel via a wet sol-gel method. A water like solution of several chemicals is prepared which gels after some time, fixing the stirred in ferroelectric particles in space and, after setting yields a solid material which, when illuminated by infrared laser light glows green. Embedding ferroelectric particles is challenging: density differences to the matrix fluid lead to sedimentation, small particles undergo agglomeration and this causes enhanced sedimentation. Microgravity avoids disturbing effects and using a suitable dispersing chemical, agglomeration can be avoided. Thus, ferroelectric aerogels with improved optical properties can be achieved in this experiment.
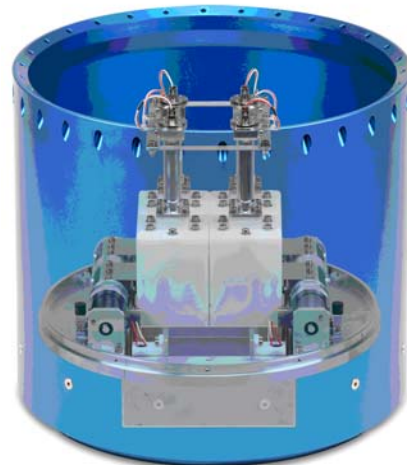

Figure 8: Transparent Photo of the Aeroget Module [6]

4.6. IGAS

The IGAS module was developed at the DLR Mobile Rocket Base and consisted of an intelligent antenna and a standard antenna system with the appropriate GPS receivers. In the flight module (IGAS) there are two GPS receivers. The first one is used as a reference module,

without antenna switching. All IGAS data is collected and sent via RF link to ground. On ground, the data are received, monitored, and archived by the ground system.

The block diagram in Figure 9 shows the structure the IGAS system which has been flown successfully on the REXUS-4 and MAPHEUS-1 missions.

The four flight antennas are combined by the 4 port coupler. The output signal of the coupler is amplified by a low noise preamplifier which is supplied by the bias line. This amplified signal is connected by a pin diode switch to the GPS receiver number 2. The pin diode switches select between both antenna quartets. The first GPS receiver is permanently connected to the first flight antenna quartet.
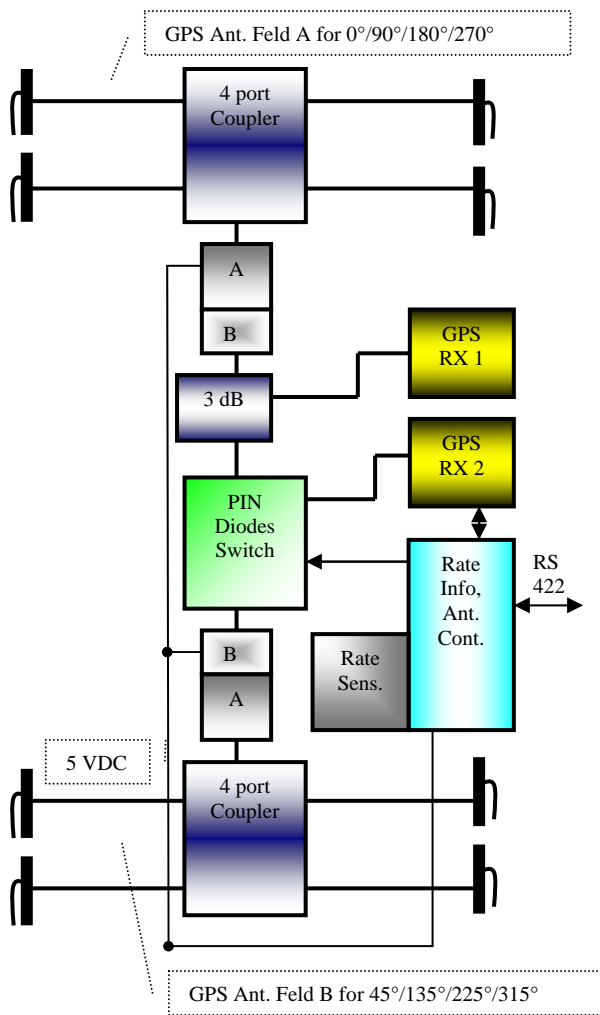

Figure 9: IGAS Block Diagram [5]

By the means of the rate gyro the on-board computer switches the antenna quartets depending on the spin rate of the sounding rocket. During one rotation of the rocket,

the on-board computer switches 8 times from one antenna quartet to the other.

The on-board computer and the software of the GPS receiver were tested on a rate table. The resulting improvements were implemented into the GPS computer. The most important improvement was change from pure phase-lock-loop to frequency-lock-loop synchronisation. This change has stabilized the GPS system. More information can be found in [5].

The NEO Freerunner experiment was also integrated in the IGAS module which is an experiment to measure the performance and accuracy of MEMS accelerometer Ics under heavy static loads.

5. FLIGHT PERFORMANCE

MAPHEUS-1 was launched from Esrange, Sweden on the 22nd of May 2009 at 10:32 UTC. The ATLAS-M and ARTEX-M experiments started 20 min before lift-off to heat the metallic samples, so that they were liquid during the microgravity phase. In the ascent phase of the rocket, the maximum acceleration of 21 g was reached after 2.4 s and the burn-out of the 1st stage was 3.4 s. Exactly 8.7 s after lift-off, the second stage (an Improved Orion motor) ignited.
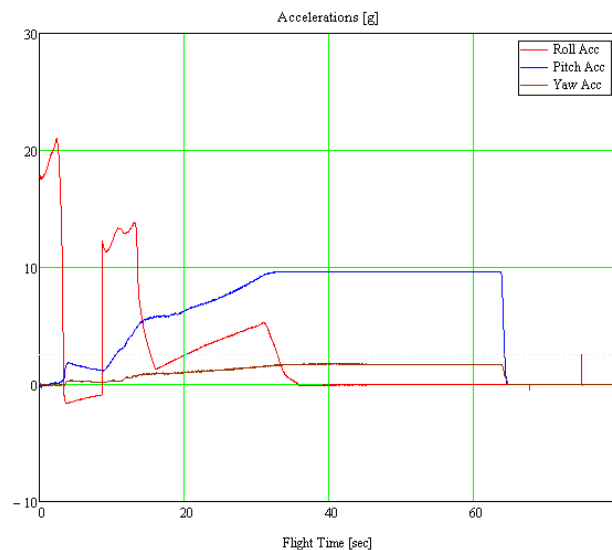

Figure 10: Accelerations during Ascent Phase

Figure 10 shows the acceleration phases of both motors and the coast phase of about 5 seconds in between. Additionally, the two different acceleration phases during the boost phase of the second stage are visible.

The blue and the brown curves indicate the centrifugal accelerations because of the spin of the rocket. As the sensors are installed asymmetrically there are noticeable two different levels of acceleration. Both curves can be

used to recalculate the spin frequency of the rocket as the roll rate sensor goes into saturation at rates higher than 983.04 °/sec. The drops of both curves are forced by the activation of the yo-yo system, whereby the spin rate of about 4.5 Hz is reduced to almost 0 Hz.

The small drop of the roll acceleration at 67.6 seconds is caused by the nose tip ejections, while the acceleration peak at 74.75 sec is due the motor separation [2].
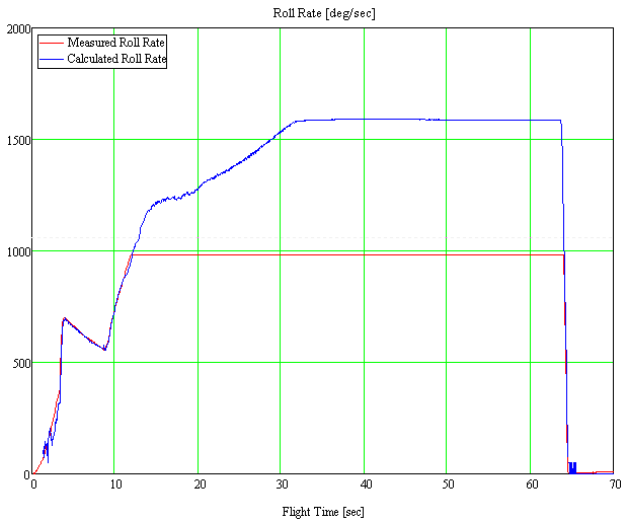

Figure 11: Roll-Rate During Ascent Phase as Function of Flight Time

At an altitude of 70.2 km a yo-yo system decreased the rotation of the vehicle around its longitudinal axis, which was spin-stabilized during the ascent. The yo-yo system worked for 0.8 seconds and reduced the roll rate from 1612 °/s to 7 °/s. The roll-rate is shown in Figure 11. At an altitude of 74.5 km the nosecone was jettisoned. The 2nd stage motor was separated from the payload at 74.7 s at an altitude of 82.3 km.
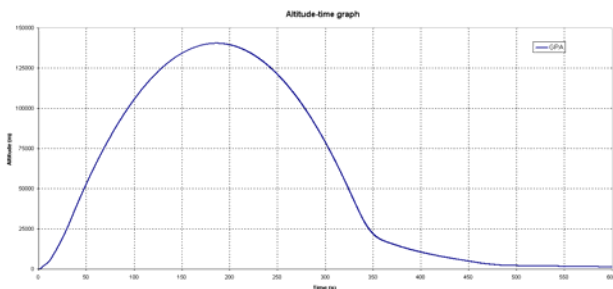

Figure 12: Altitude vs. Flight Time

The activation of the RCS-System was done by timeline at 81 s and within 1.8 s the already small roll-rate was reduced to less than 0.2 °/s hence microgravity conditions for the payload were achieved already at 96.1 km at the ascent. The payload reached an apogee of 140.8 km at

186 s. Figure 12 shows the trajectory of the MAPHEUS-1 vehicle.

At flight time 276 s the vehicle entered the higher density of the atmosphere at 102 km and the RCS automatically started to spin up the payload at 298 s for the re-entry. The constraint of 3 minutes of experiment phase time was therefore exceeded by 8 seconds.

After the experiment phase, the payload re-entered the atmosphere and was decelerated by the aerodynamic drag. The maximum deceleration of about 7 g during the descent occurred at 22 km altitude. The accelerations during re-entry are shown in Figure 13.
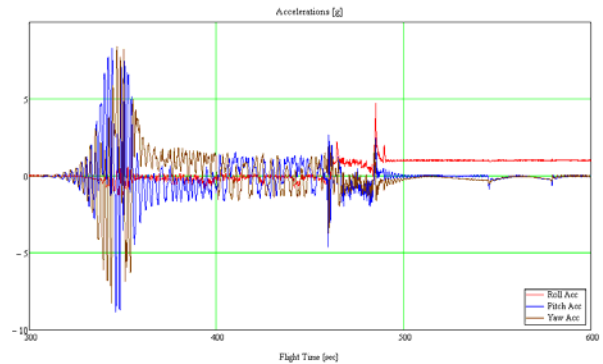

Figure 13. Roll, Yaw and Pitch Acceleration During Re-Entry as Function of Flight Time

The heat shield, stab-chute and beacon of the recovery system were activated at 4.6 km altitude. The stab-chute was de-reefed 5 seconds later and the main chute released at 3.1 km altitude. The payload landed safely on ground and was recovered by the helicopter and brought back to Esrange one hour later in excellent condition.

No.	Time [s]	Alt [km]	Event
1	T-120 min	0.332	Experiments Power On (except RAMS)
2	T-113 min	0.332	ARTEX-M / ATLAS-M Valve Open (inside module)
3	T-25 min	0.332	Switch from Hardline to RF
4	T- 25 min	0.332	Experiments Power On (RAMS)
5	T- 20 min	0.332	Possible Hold
6	T- 20 min	0.332	ARTEX-M / ATLAS-M Heating by FPGA/cRIO
7	T-358.3	0.332	TV TX On
8	T-300.0	0.332	Internal Power
9	T-120.0	0.332	RAMS Battery On
10	T- 60.0	0.332	RAMS Start of Data

			Storage
11	T- 30.0	0.332	ATLAS-M Power switch to Internal Batteries
12	T- 11.0	0.332	ARTEX-M / ATLAS-M Vacuum Valve closed (inside Module)
13	T- 10.0	0.332	ARTEX-M / ATLAS-M Vacuum Valve closed (part of GSE)
14	T- 9.0	0.332	ARTEX-M / ATLAS-M Venting Valve open to vent hose (part of GSE) -> hose separates from Umbilical
15	T+ 0.0	0.332	Lift-Off
16	T+ 0.0	0.332	ATLAS-M Lift-Off Signal
17	T+ 0.0	0.332	RAMS Lift-Off Signal
18	T+ 0.0	0.332	IGAS Lift-Off Signal
19	T+ 2.4	0.750	Max. Acceleration (21.04 g)
20	T+ 3.4	1.230	Burnout 1st Stage (Nike)
21	T+ 8.7	4.150	Ignition 2nd Stage (Imp. Orion)
22	T+ 35.8	33.950	Burnout 2nd Stage (Imp. Orion)
23	T+ 63.7	70.200	YoYo De-spin
24	T+ 66.0	73.000	ATLAS-M SOE (on)
25	T+ 67.0	73.510	GPS Antenna Switch
26	T+ 67.6	74.500	Nosecone Separation
27	T+ 74.8	82.300	Motor Separation
28	T+ 80.0	87.290	AEROGET SOE (on)
29	T+ 81.0	88.700	RCS Activation
30	T+ 81.0		ARTEX-SOE (micro-g detection on)
31	T+ 82.8	90.400	End of first Acquisition (rates < 0.2°/s)
32	T+ 88.8	96.100	Microgravity achieved
33	T+100.0	105.330	AEROGET SOE (off) (20 s after SOE on)
34	T+186.0	140.800	Apogee
35	T+248.0	121.300	ATLAS-M SOE (off) (30s before Re-entry)
36	T+268.0		Re-entry Detection Mode On
37	T+276.8	102.100	End of microgravity
38	T+278.0	99.340	Begin of Atmospheric Re-entry
39	T+298.0	81.800	Re-entry Mode, Spin-Up by RCS
40	T+459.3	4.7 km	Heat shield, Stab Chute Activation + Beacon Activation
41	T+464.3	4.2 km	Stab Chute De-Reefing
42	T+483.2	3.0 km	Main Chute Activation
43	T+489.0	2.9 km	Main Chute De-Reefing
44	T+580.0		RAMS SOE Off (Battery Off)
45	T+600.0	2.0 km	Power Off for Experiments
46	T+1000.0	~0.6 km	Power Off TM/TV

Table 6: MAPHEUS-1 Time Events

6. SUMMARY & OUTLOOK

The MAPHEUS-1 rocket was financed from the DLR research and development programme "Space". The material physics experiments were designed and built at the DLR Institute of Material Physics in Space in Cologne. The DLR Mobile Rocket Base in Oberpfaffenhofen was responsible for all flight hardware and the launch campaign. The project management was lead by the DLR Institute of Space Systems in Bremen.
MAPHEUS will be launched in a regular annual programme to enable a systematic study of material science.

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