MAPHEUS-1: VEHICLE, SUBSYSTEM DESIGN, FLIGHT PERFORMANCE AND 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.
This paper gives an overview on the MAPHEUS-1 vehicle, the experiments, the successful maiden flight of the rate-control-system and the campaign. The paper includes first flight results and it 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.

Table 1. The MAPHEUS-1 Schedule

Milestones	Date
Kick-Off Meeting at DLR Cologne	2008-06-18
Status Meeting at DLR Oberpaffenhofen	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

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

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

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.

2. THE VEHICLE DESIGN

MAPHEUS-1 was a two-stage unguided solid propellant sounding rocket similar to REXUS-4 [8]. 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.

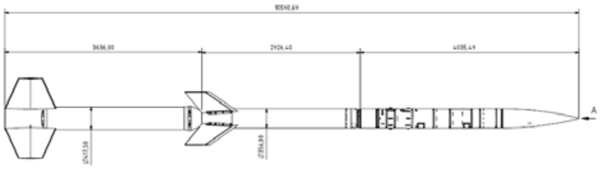

Figure 1. MAPHEUS-1 two-stage unguided solid propellant sounding rocket [7]

The payload is based on modules with 356 mm diameter, which are also used in the REXUS project.

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 center of gravity during lift-off that has to be ahead of the center of pressure.
The center 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 [7].

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 has not been a scientific reason 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 center 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.

Table 2. The MAPHEUS-1 Mass Budget [7]

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**

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.

Table 3. The Service System Frequency List [7]

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 4. The IGAS Experiment Frequency List [7]

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

Table 5. The Recovery System Frequency List [7]

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

3. DEVELOPMENT OF RCS SYSTEM

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, see Figure 2) 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].

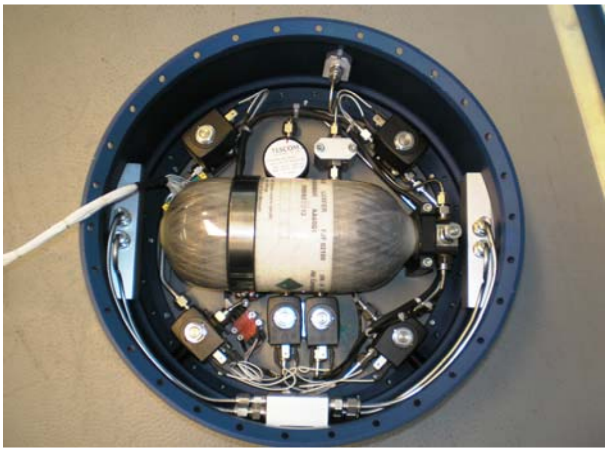

Figure 2. Top View of the RCS Module [1]

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 **Ge**la**t**ion), 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).

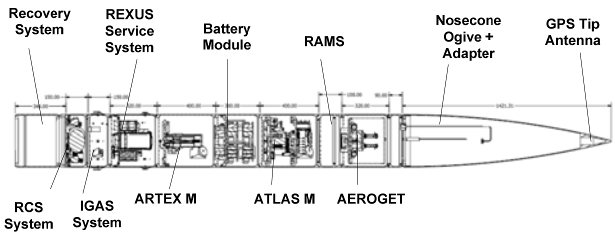

Figure 3. Sketch of the MAPHEUS-1 Payload [7]

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.

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. 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.

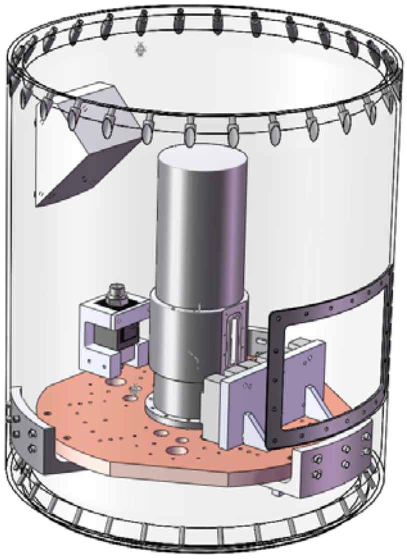

Figure 4. Sketch of the ARTEX-M Module [6]

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.

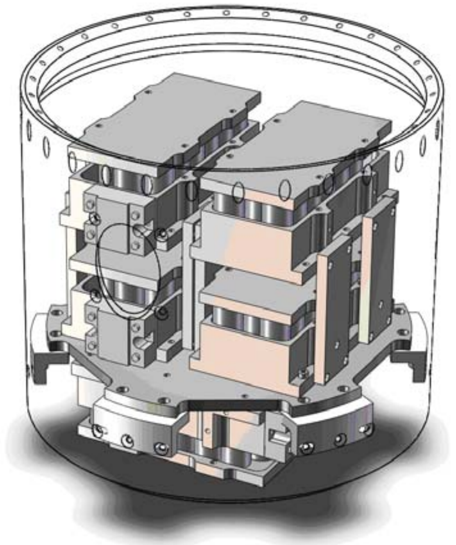

Figure 5. Sketch of the BATT-M Module [3]

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.

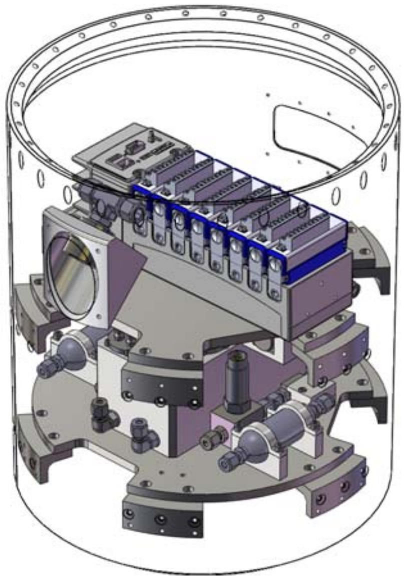

Figure 6. Sketch of the ATLAS-M Module [2]

4.4. RAMS

During the sub-orbital rocket flight we have different levels of accelerations. 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 flown 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 gel after some time, fixes the stirred in ferroelectric particles in space and after drying yields a solid material which upon illumination 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 then enhanced sedimentation. Microgravity avoids all disturbing effects and using a suitable dispersing chemical agglomeration can be avoided. Thus ferroelectric aerogels with improved optical properties shall be achieved in this experiment.

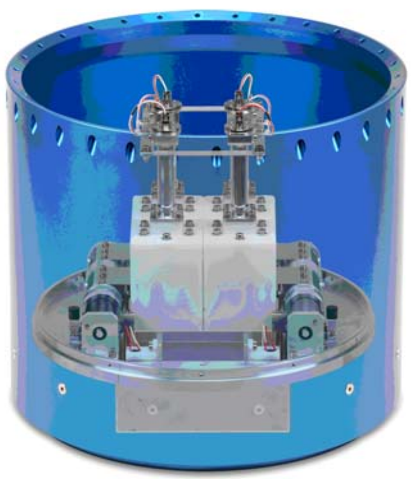

Figure 7. Transparent Photo of the Aeroget Module [5]

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 receiver. The first one is used as a reference module, without antenna switching. All IGAS data are 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 8 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.
By the means of the rate gyro the board computer switches the antenna quartets depending on the spin rate of the sounding rocket. During one rotation to the rocket the board computer switches 8 times from one antenna quartet to the other.
The 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 [4].
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.

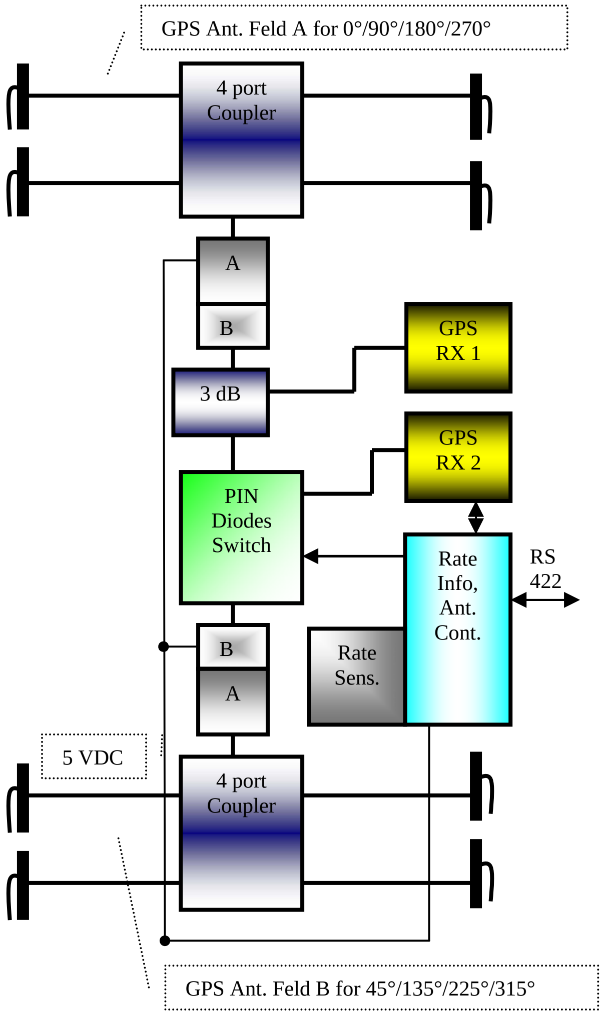

Figure 8. IGAS Block Diagram [4]

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 samples to have liquid metals during the microgravity phase. In the ascent phase of the rocket the maximum acceleration of 18.9 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, ignites. At an altitude of 70.4 km a yoyo system decreases the rotation of the vehicle around its longitudinal axis, which is spin-stabilized during the ascent. The roll-rate is shown in Figure 9. At an altitude of 74.6 km the nosecone was jettisoned. The 2nd stage motor was separated from the payload at 75 s in an altitude of 83 km.

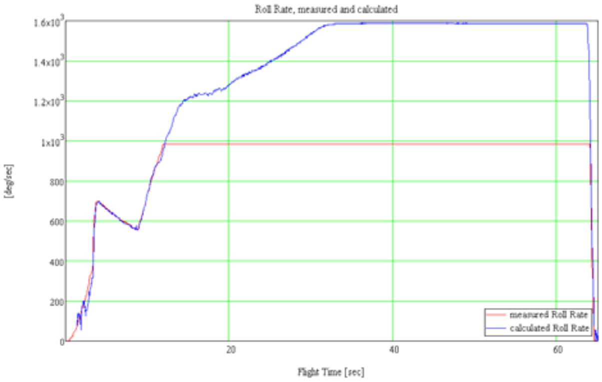

Figure 9. Roll-Rate during Ascent Phase as Function of Flight Time

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 2 °/min hence microgravity conditions for the payload were achieved already at 90.6 km at the ascent. The payload reached an apogee of 140.8 km at 186 s. Figure 10 shows the trajectory of the MAPHEUS-1 vehicle.

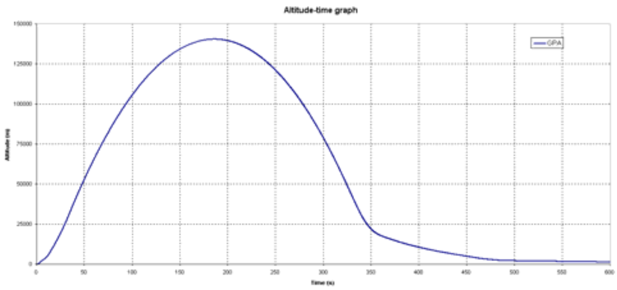

Figure 10. Altitude vs. Flight Time

At flight time 293 s the vehicle entered the higher density of the atmosphere at 87 km and the RCS automatically started to spin up the payload at 297 s for the re-entry. The constraint of 3 minutes of experiment phase time was therefore exceeded by half a minute.

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 11.

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.

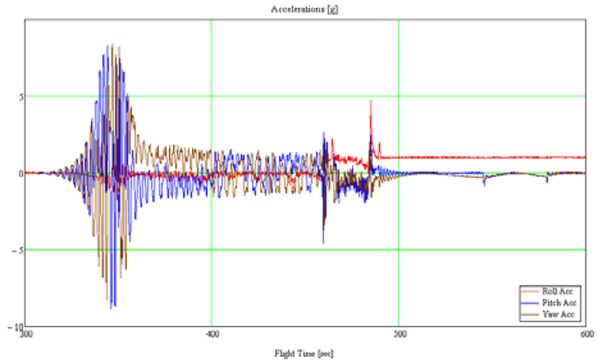

Figure 11. Roll, Yaw and Pitch Acceleration during Re-entry as Function of Flight Time

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.

7. REFERENCES

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