MATERIAL PHYSICS ROCKETS MAPHEUS-3/4: FLIGHTS AND DEVELOPMENTS

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ABSTRACT

Sounding rockets can serve as a time- and cost-effective platform for a wide range of research under microgravity conditions. It is shown that MAPHEUS – *Ma*terial*Ph*ysikalische *E*xperimente *U*nter *S*chwere-losigkeit (Materials Physics Experiments under Weightlesness) – a DLR internal R&D project perfectly achieves this whilst maximizing scientific output. MAPHEUS hereby offers launch opportunities on a yearly basis and with comparatively short development cycles of about one year only. In the first three campaigns MAPHEUS provided about three minutes of microgravity time. Recent developments enable to extend this to four minutes above 100 km. Performance data of the recent MAPHEUS-3 flight together with information on the experiment modules are provided. Further an outlook is given on the experiment modules used on board of MAPHEUS-4 and the new vehicle.

1. INTRODUCTION

Sounding rockets enjoy wide adoption as a measurement platform for atmospheric physics and as a microgravity platform for experiments from different science disciplines. Several microgravity research rockets are available to the scientific community, typically run on a national basis, as European collaboration through ESA, or as an international collaboration. Prominent examples are the sounding rocket programme TEXUS run by the German Space Agency with the prime contractor ASTRIUM and the ESA led sounding rocket programme MASER with the prime contractor SSC as well as MAXUS with the prime contractor ASTRIUM. The former two sounding rocket programmes offer microgravity times of about six minutes whereas MAXUS offers up to 12 minutes. The programmes have in common that they are operated at bi- but more common only on multi-annual intervals, which means relatively long development cycles for experiments. The project management is carried out by the prime contractor and experiment modules are built by the prime contractor and industrial subcontractors. Different to the mentioned programmes the MAPHEUS sounding rocket project is an internal DLR R&D project. The scientific experiment facilities for MAPHEUS are selected, designed and built by the DLR Institute of Materials Phyics in Space. The Mobile Rocket Base (MORABA) of DLR is responsible for the provision of rocket motors and the service-, rate-control-, and recovery systems. The overall project is managed by the DLR Institute of Space Systems. The operational launch services are carried out by DLR MORABA together with SSC at ESRANGE Space Center Kiruna, Sweden.

MAPHEUS solely focuses on materials physics payloads. The setup of the project within DLR R&D allows for extremely rapid development cycles, yielding cutting-edge scientific return and short lead times. Technical limits of experiment facilities can be pushed as new developments are incorporated into MAPHEUS in a flexible manner. A particular strength of the project is to enable also systematic materials investigations, where a large number of samples and step-wise parameter variation are required. This is realized through yearly launches and re-flights of refurbished and/or upgraded experiment facilities.

The concept of a rapid-development and boundary-pushing research rocket falls in line with the relatively short microgravity time of only up to four minutes and a strong educational component within the project evidenced by bachelor, master, diploma, and doctoral thesis work both in engineering as well as physical sciences.

The following sections present the experiments, vehicle and flight of MAPHEUS-3, launched successfully on 25th November 2013 at 12.20 LT. Furthermore, the scientific and technical plans for MAPHEUS-4 are introduced.

2. MATERIAL PHYSICS ON MAPHEUS

Experiments on MAPHEUS 1-3 have covered a wide range of material physics research areas. Dedicated systems were built to investigate the gelation for forming of light-weight porous materials, the behaviour of granular gases, the diffusion in liquid metals [1], the solidification of alloys [2], and the demixing of undercooled melts. All design is carried out with a focus on maximizing the number of investigated material samples and thereby the overall scientific return. Further, to be cost-effective the experiment module design is done such as to allow for reusability with minimal refurbishment. Performing materials research on liquid metals with the aim to elucidate their solidification, diffusion, and demixing behaviour requires high temperatures to be achieved. As a result high power is needed to be able to operate a large number of furnaces simultaneously and to prevent the materials from oxidation high vacuum-conditions have to be maintained during the flight.

3. MAPHEUS-3 EXPERIMENTS

As shown in Fig. 1 MAPHEUS-3 was launched successfully on 25 November 2012 at 12.20 LT. Propelled by a two-stage Nike/Improved-Orion motor combination, the flight offered more than three minutes of less than 10^{-4} g.

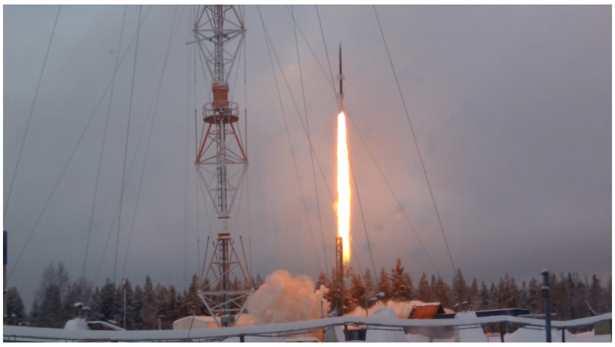

Figure 1. MAPHEUS-3 lifting off from ESRANGE

The investigated physical phenomena on MAPHEUS-3 included atomic transport processes in liquid alloys with the goal of determining diffusion coefficients (ATLAS-M); the demixing of copper-based metallic alloys during controlled cooling (DEMIX-M); and the behaviour of magnetically-excited granular matter (MEGraMa-M); a shear-cell furnace (SCID-M) serving both as a precursor experiment for the upcoming MAPHEUS-4 campaign as well as to study impurity diffusion in liquid Al base alloys. ATLAS-M, MEGraMa-M, and DEMIX-M were experiments with flight heritage, but have been upgraded, whereas SCID-M was a completely newly developed facility. For delivering power to the experiments the BATT-M module was used.

ATLAS-M (Atomic Transport in Liquid Alloys and Semiconductors, Fig. 2) is a module dedicated to the determination of diffusion coefficients. It enables to simultaneously process 32 diffusion samples in eight independently operated furnaces. The module and furnace design is in detail described in [1]. On MAPHEUS-3 self-, impurity, and chemical diffusion in liquid Al base alloys were successfully investigated. The furnaces nicely followed the set heating profiles. A net diffusion time of up to 140s was achieved depending on the samples liquidus and solidus. Preliminary data analysis of some of the samples showed excellent agreement with model predictions clearly indicating that due to the excellent thermal stability Marangoni flow did not disturb the diffusion process.

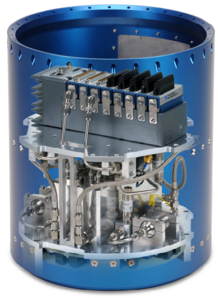

Figure 2. ATLAS-M in its experiment module

DEMIX-M (Fig. 3) is a module dedicated to the investigation of the demixing behaviour of undercooled Cu-Co melts. DEMIX allows to simultaneously operate eight furnaces arranged in two independent furnace compartments. The furnaces can be operated at temperatures of up to 1500°C. The module further enables very fast heating to maximize the microgravity time available for sample cooling. The spherical Co-Cu samples are embedded in liquid Duran glass. Heterogeneous nucleation is hereby suppressed and the liquid samples can be cooled below their liquidus. To avoid foaming of the Duran the furnaces are processed under Argon atmosphere. For fast cooling a Ar/He gas mixture is used. Preliminary data analysis showed that four of the eight samples were well homogenized during heating and showed phase separation during cooling. The MAPHEUS data complement earlier data obtained on the sounding rocket TEXUS and drop-tube experiments where the samples have been freely suspended by electromagnetic levitation and droplets have been formed through liquid injection, respectively [3].

Figure 3. DEMIX-M experiment

SCID-M is an experiment facility introducing a novel shear-cell furnace for X-ray radiography to microgravity applications. SCID-M is integrated into the other half of the DEMIX-M module. The compact shear cell furnace which is at the heart of the SCID-M facility (Fig. 4) is in detail described in [4]. The most recent update to be used in the MAPHEUS-4 campaign is described in [5] as are *in-situ* ground-based experiments in [6].

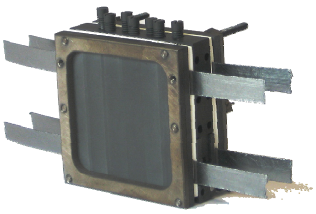

Figure 4. The shear-cell furnace of the SCID-M experiment, now employed in MIDAS-M on MAPHEUS-4

Fig. 5 shows an X-ray radiograph before shearing (left) and after shearing (right) to illustrate the working principle. In this shear-cell, the individual alloys samples are melted separately. After homogenization different samples constituting a diffusion pair are brought into contact with each other by shearing half of the furnace. Hereby the diffusion process is started at a well-defined time.

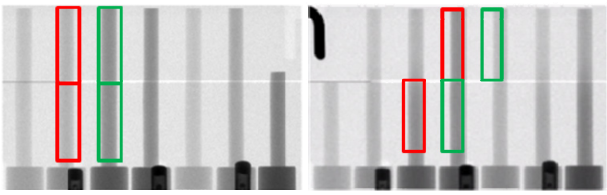

Figure 5. Working principle of the shear cell. Red and green outlines indicate different metals sheared into contact after melting.

On MAPHEUS-3 the shear-cell was cooled down to solidify the samples under microgravity. Heating and cooling as well as shearing under microgravity worked nominally. Even so the samples have been liquid already during ascent in the hyper-g phase no sample leakage from the capillary compartments was observed. Hence, diffusion time can also be maximized in future sounding rocket missions by melting the sample already in hyper-g conditions, which is due to convective flow an effective means for sample homogenization.

MEGraMa-M (Magnetically Excited Granular Matter) builds upon previous experiments in parabolic flights and drop-tower shots for observing the cooling of a magnetically excited granular gas with a high-speed camera system (Fig. 6). The system consisting of paramagnetic spherical particles is excited homogeneously and monitored by high-speed imaging at 500 fps. Particle positions and velocities can be extracted and compared to theoretical predictions both for the steady state as well as for cooling once agitation is switched off. While in the drop tower experiments already the initial stages of cooling of the gas were observed, the sounding rocket experiment enables to follow granular cooling towards much longer times. At the same time, the rocket experiment also provides access to the study of granular clustering. In addition to MAPHEUS-3 where only a single camera was used, the re-flight on MAPHEUS-4 is performed with an updated recording unit and a second camera system. In addition to enhanced reliability, with images from both cameras particle tracking in 3D becomes possible.

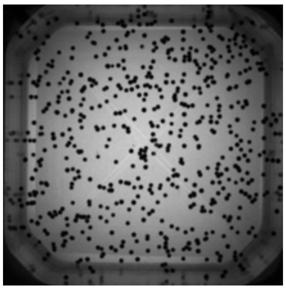

Figure 6. Excited granular gas as investigated in MEGraMa-M

4. MAPHEUS-3 VEHICLE AND FLIGHT

MAPHEUS-3 was propelled by a two-stage Nike/Improved Orion motor combination, reaching an apogee altitude of 140 km with an overall payload mass of 195 kg. This comprised a 110 kg scientific payload and 85 kg of rocket systems (recovery-, rate-control-, and service system, among others). An overview of the payload stack including dimensions is given in Fig. 7. MAPHEUS currently uses standard 356 mm (14 inch) diameter experiment modules.

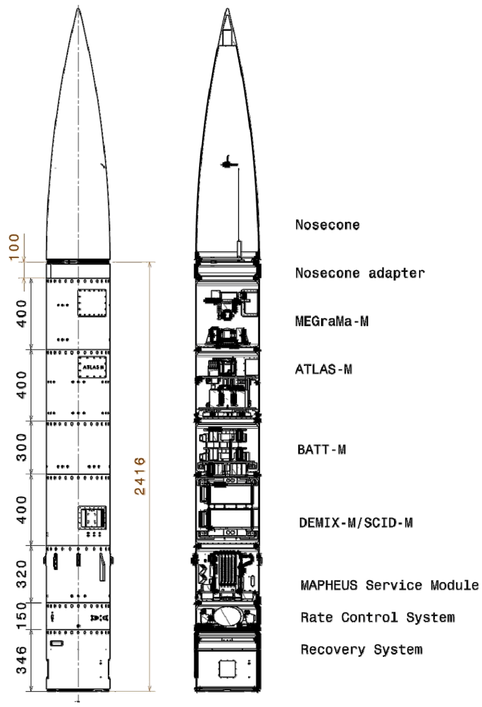

Figure 7. Overview of the MAPHEUS-3 payload stack

After a flight time of approximately 80 s, the stabilizing 4 Hz roll rate of the ballistic vehicle was compensated by a yo-yo despin system; residual rates and accelerations were suppressed by the MORABA-developed rate-control system [7]. Excellent experiment conditions in terms of accelerations (in the order of 10^{-5} g) and rotational rates were achieved (Figs. 8 and 9).

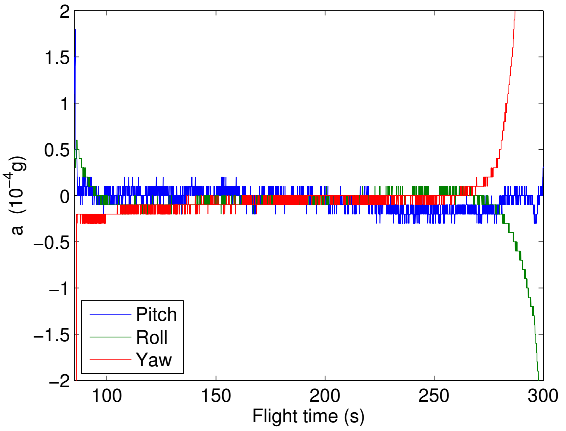

Figure 8. Accelerations in three axes after activation of the rate-control system.

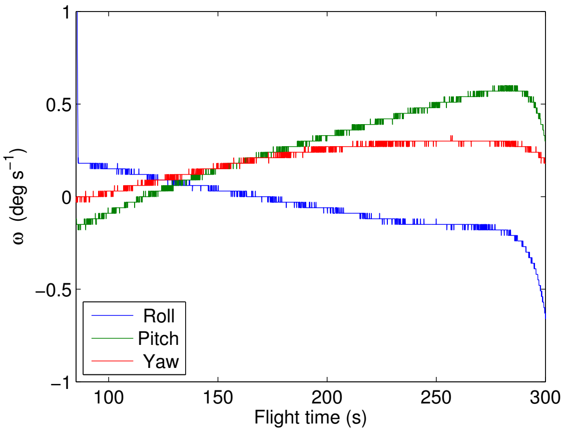

Figure 9. Residual rates after rate-control system activation.

5. MAPHEUS-4 EXPERIMENTS

MAPHEUS-4 is scheduled for launch in July 2013. Its scientific payload will combine a shear-cell furnace with *in-situ* X-ray radiography to achieve time-resolved measurements of diffusion processes (MIDAS-M experiment). The new experiment facility is complemented by a change of rocket motor to ensure up to four minutes of high-quality microgravity measurement time.

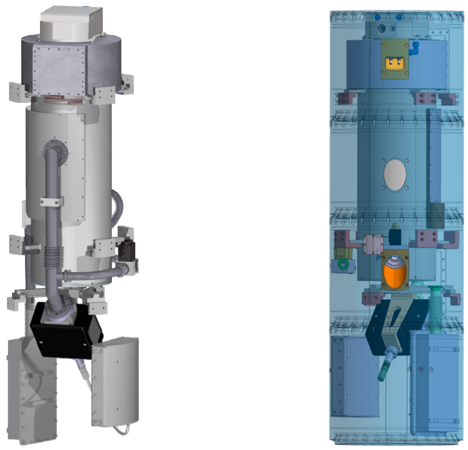

Figure 10. X-ray radiography facility MIDAS-M with sample chamber (top), X-ray tube, and ion-getter pump (bottom).

For use on research rockets, the DLR Institute of Materials Physics in Space has custom-equipped the X-ray tube with an ion-getter pump to sustain ultra-high vacuum levels from lift-off throughout the flight.
For future MAPHEUS-flights, re-flights of the same radiography facility are foreseen, potentially applied to different materials physics research areas [8]. On MAPHEUS-4, MIDAS-M will be complemented by an extended version of MEGraMa-M in the scientific payload stack.

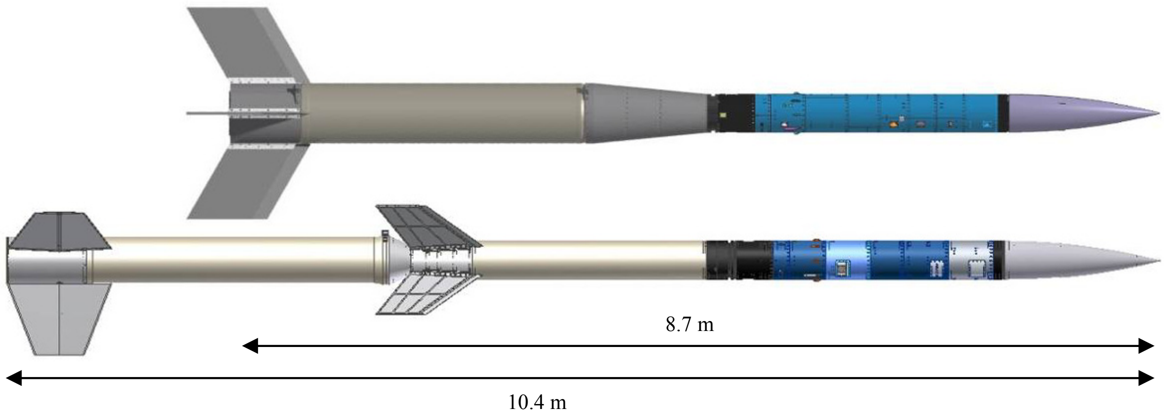

Figure 11. The MAPHEUS-4 (top) and MAPHEUS-3 (bottom) vehicles with motor(s), motor adapter and payload sections (blue).

6. MAPHEUS-4 VEHICLE

An increase in scientific payload mass with MIDAS-M is one of the reasons for employing a new motor system on MAPHEUS-4. The Nike/Improved-Orion combination of the three previous MAPHEUS flights is replaced by a S30 motor, introduced for the first time by DLR MORABA in this single-stage configuration. Its use allows maintaining close to four minutes of experiment time above 100 km. The configuration of the payload section in terms of rocket systems and module dimensions follows the standard MAPHEUS specification (Fig. 11).

7. CONCLUSION AND OUTLOOK

MAPHEUS-3 and previous flights have returned a wealth of material physics samples and allowed for a systematic investigation of diffusion coefficients and miscibility behaviour of metallic alloys. From MAPHEUS-4 onwards, X-ray radiography will open a new window by allowing direct *in-situ* observations. With a change of motor from Nike/Improved-Orion to single-stage S30, a sustainable solution offering four minutes of experiment time is provided to the project.

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