THE ROLE OF SOUNDING ROCKET MICROGRAVITY EXPERIMENTS WITHIN THE GERMAN PHYSICAL SCIENCES PROGRAMME

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ABSTRACT

The German Physical Sciences Programme, managed by the German Space Agency DLR, deals with investigations of the effects of weightlessness ("microgravity") on physical and chemical processes and phenomena. The research priorities concern materials design from the melt, fluid flow dynamics, basic mechanisms of combustion processes, and fundamental particle interactions. For achieving progress in these domains DLR cares for the infrastructure required, i.e. appropriate research facilities and flight opportunities for microgravity experiments, and provides the necessary add-on funding for scientists at universities and other research institutes. Within the new German Space Programme, approved by the government in May 2001, sounding rocket flights for microgravity experiments are an essential part in pursuing the programmatic goals.

In retrospect, using different flight opportunities, in total more than 600 microgravity experiments involving German principal investigators in the field of physical sciences were performed till now. It turns out that more than a quarter of them flew on sounding rockets. Among the different rocket types used the TEXUS carrier proved to be the "workhorse" of the huge majority of the German experiments during three decades.

Some characteristic examples of facility developments and experimental results are given to highlight the pioneering gain of knowledge using sounding rocket flights. Featuring their own scientific goals such experiments are self-standing and on the other hand expected to be also complementary to the increased ISS utilization in the upcoming years.

1. INTRODUCTION

The German Physical Sciences Programme is managed - like all other activities in Germany - by the German Aerospace Center, DLR. This assignment is in addition to its important role as a major research establishment in the areas of aeronautics, spaceflight, transport and energy. As such DLR has three major responsibilities:

- to establish the German Space Programme on behalf of the German government with its three integral parts: the German participation in the European programmes of ESA, the national programme, and the DLR intramural R & D programme of the corresponding research institutes
- to implement the programme by placing contracts to industry for development of experiment facilities, by providing flight opportunities, and by funding of research activities at universities and other research institutes
- to establish international coordination (bi- and multilateral) in the field of space research.

Based on the government's political objectives a new space programme was established and finally approved by the German government in May 2001. To expand the knowledge on the Earth including its living systems and the outer space through "best science" research as well as to ensure industrial growth and to establish value added chains are among the top level goals. In addition, the innovative potential of space utilization is to be exploited, and young people should be inspired for science and engineering. To these top level goals the Physical Sciences Programme has to and will make substantial contributions.

2. OVERALL PROGRAMME STRUCTURE

The Physical Sciences Programme as such is part of the national programme Research under Space Conditions, which also covers the Life Sciences Programme. The national programme is complementary to and closely coordinated with the corresponding ESA programmes. In reality, the national programme in the field of physical sciences is based on a large extend on bilateral and multilateral research co-operations with e.g. USA, Russia, France, and Japan.
The programme Research under Space Conditions is characterized by three elements:

- **EXPERIMENTS**, which cover the funding of scientists for preparation, performance and analysis of microgravity experiments
- **FACILITIES**, which comprise the development of research instruments for flight opportunities provided nationally, by ESA or other agencies, as well as related user support activities implemented by the German user operations centre MUSC
- **MISSIONS**, which concern the procurement or bartering of national or other agencies’ flight opportunities for suborbital and orbital missions.

In 2005, the expenditures for microgravity activities in the national programme amounted to some 15 M€ with an equal share for activities in physical and life sciences. In total, Germany’s expenditures for microgravity related activities amount to about 6% of the overall space budget.

### 3. PAST MICROGRAVITY EXPERIMENTS

#### 3.1 Share in flight opportunities

In order to judge the role of sounding rocket missions within the field of physical sciences their share in different flight opportunities covering almost 30 years of German microgravity experiments has to be analyzed. On manned orbital missions, such as US Shuttle, Spacelab, Spacehab, Soviet/Russian space stations Salyut and MIR, and the ISS, 22% of all physical sciences experiments were performed. As shown in Fig. 1, among the remaining part of experiments that have been flown on unmanned/suborbital missions since 1975,

![Figure 1](image)

**Fig. 1. Share of performed German microgravity experiments using different flight carriers**

sounding rocket flights amount to 29%. Both ballistic airplane missions and free fall capsules at drop towers/shafts/balloons contributed to about 20%. Long duration experiments on unmanned orbital missions, like EURECA, FOTON, and GAS, summarize to 9%. In fact, each of these flight opportunities provides specific experimental conditions. Nevertheless, the statistics demonstrates that a very significant part of all scientific investigations could be performed on sounding rockets and underlines their importance in the overall context of the microgravity activities.

#### 3.2 Share in research disciplines

Among the four research disciplines (materials research, fluid physics, combustion, fundamental physics), which cover all German microgravity experiments in physical sciences, 52% of the investigations were performed in the domain of materials research so far. It follows fluid physics (36%), fundamental physics (8%), and combustion (4%).

In comparison to that, the share of materials research and fluid physics experiments with respect to sounding rocket missions is even more pronounced with 58% and 40%, respectively. No German experiments on rockets were performed in the discipline combustion, but a few in fundamental physics (2%).

#### 3.3 Annual distribution of all experiments

Since 1975, Germany has performed practically each year microgravity experiments in physical sciences, which leads to a total number of 644 experiments. As shown in Fig. 2, the annual frequency of experiments significantly varies over the years with peaks in 1983 and 1985, the first Spacelab and the German D-1 Spacelab mission.

![Figure 2](image)

**Fig. 2. Annual number of performed German microgravity experiments in physical sciences**

After the first Shuttle accident it took a longer period of significantly less performed experiments before the German D-2 Spacelab mission could be launched in 1993. In the same year, the European retrievable research platform EURECA was deployed into orbit for 6 month, which resulted in a peak of altogether 53 performed experiments in 1993. Obviously, with beginning of the 90’s a rather high mean level in the order of 30 experiments per year could be maintained till now. Therefore, more than two thirds of all performed experiments fall in the share of the last 14 years. In fact, this is mainly due to the increased number of suborbital missions.
3.4 Annual distribution of sounding rocket experiments

Until the end of the 80’s sounding rocket flights provided the vast majority of all German unmanned missions. As shown in Fig. 3, in the 80’s about 10 to 15 German sounding rocket experiments per year could be implemented. Later on, the availability of unmanned flight opportunities was enlarged by the Drop Tower Bremen (1991) and Russian re-entry satellites FOTON (1991). Moreover, the number of parabolic airplane flights was increased, especially by using the Airbus A-300 via ESA or nationally. Subsequently, the frequency of sounding rocket experiments has decreased in the last years. This fact is also due to constant or even smaller budgets for such research activities at ESA and DLR.

![Graph showing annual number of German microgravity experiments on sounding rockets](image)

Fig. 3. Annual number of German microgravity experiments on sounding rockets

But in contrast to other flight opportunities, like for instance Spacelab missions (1983-1998), microgravity research on rockets could continuously be implemented at a nearly annual basis over 3 decades.

3.5 Share in different sounding rocket types

The German utilization of sounding rockets for physical sciences experiments started in 1975 in collaboration with NASA, i.e. the very early years of microgravity investigations at all. Three experiments flew in 1975-78 within the NASA rocket programme SPAR. In 1977, the German sounding rocket programme TEXUS materialized by the first launch of a full physical sciences payload consisting of 11 individual experiments. In the following years, almost each of the 41 launched TEXUS rockets carried German experiments in the field of physical sciences.

Beginning in 1987, German experiments were also flown on rockets with a similar flight characteristics within the MASER programme of ESA. The German utilization of MAXUS and Mini-TEXUS rockets started in 1992 and 1993, respectively. In 1995, the Russian ballistic rocket VOLNA was used by DLR for a special experiment that required some more microgravity time than available on other existing sounding rocket types. For the first time, this rocket was launched from a submarine for a research mission, carrying 100 kg of scientific payload on a ballistic trajectory over 5600 km, and provided 20 minutes of microgravity time. In general, the ballistic flight phases of rockets with 2 to 6 scientific payloads provide microgravity conditions ranging from 3 (Mini-TEXUS), 6 (TEXUS, MASER, SPAR), and 12 (MAXUS) minutes, respectively.

As mentioned before, it turned out that more than a quarter of all German microgravity experiments flew on rocket carriers. Among them, as depicted in

![Chart showing share of German microgravity experiments in physical sciences using different rocket types](image)

Fig. 4. Share of German microgravity experiments in physical sciences using different rocket types

Fig. 4, with a share of 87%, TEXUS proved to be the “workhorse” of the rockets used. This carrier enables a scientific payload of up to 250 kg and 6 minutes of microgravity time at a quality better than $10^{-4}$ g.

4. RECENT RESEARCH PRIORITIES

A few years ago in the course of establishing the new German Space Programme the objectives and priorities of the part physical sciences were intensively and critically discussed with experts inside and outside of space research activities. An important role played - among others - the thorough evaluation of the field by the Fraunhofer Society. Based on experiences and results of the past microgravity activities as well as taking into account the perspectives in the corresponding ground based research disciplines, the content and structure of the programme were defined.

The overall programme goal remains to gain scientific knowledge by fundamental and application-oriented research by utilizing microgravity conditions, especially onboard the International Space Station. The space programme as such opens up extended research opportunities,
first of all weightlessness during free fall conditions on different carriers, and therefore complements terrestrial research opportunities significantly.

In the last years the following research priorities of the Physical Sciences Programme were defined:

- **Materials design**: precise measurements of thermophysical properties of high melting alloys; gravity affected solidification processes
- **Structure and dynamics of fluid flow**: in configurations relevant for applications (capillaries in satellite tanks; floating zones in crystal growth processes; spherical gap like the liquid Earth’s core)
- **Basic combustion mechanisms** with respect to droplets and sprays
- **Fundamental particle interactions** in quantum, plasma, atmospheric, and astrophysical systems.

Currently, 26 scientific institutions are involved in the Physical Sciences Programme. Nearly 30 scientific projects are funded by DLR, most of them in the field of materials research and fluid physics, at an annual amount of 3.5 M€. For the development of research facilities and the procurement of flight opportunities an annual budget of 2.7 and 1.2 M€, respectively, is available.

Basically, sounding rocket flights are suitable for investigations in all four priority domains. In fact, in coordination with ESA, the German Space Agency will concentrate its next sounding rocket payloads on the research priorities of materials design and fluid flow dynamics.

5. MAIN HARDWARE DEVELOPMENTS

Mainly by means of contracts to industry DLR develops flight experiment hardware for all flight opportunities currently available. The major facility developments within the last years are

- for the Drop Tower Bremen: Advanced Disk Laser for combustion research; Bose-Einstein-Condensates facility
- for parabolic airplane flights: TEMPUS electromagnetic levitator; plasma crystal, cosmic dust, and aerosol research facility predevelopments (IMPF/ICAPS)
- for TExUS: Plasma crystal module; module for capillary channel flow investigations; aerogel solidification furnace; electromagnetic levitator for containerless processing
- for FOTON satelites: Shear cell furnace for diffusion experiments in metallic alloys
- for Shuttle GAS payloads: Spherical gap facility (the conversion into an ISS facility is currently studied)

- for the ISS: Two plasma crystal facilities, namely PK-3 and its successor PK-3 Plus, in cooperation with Russia; jointly with ESA the ElectroMagnetic Levitator EML for accommodation in COLUMBUS; the Capillary Channel Flow facility CCF in cooperation with NASA.

In the next paragraph the above mentioned TExUS research facilities and their underlying scientific experiments will be illustrated in some more detail.

6. TExUS RESEARCH FACILITIES AND ISS UTILIZATION

6.1 Plasma crystals

Plasma crystals were experimentally discovered at the Max-Planck-Institute for Extraterrestrial Physics (MPE) in 1994. Two years later the related technology was mature enough to prepare the first microgravity experiment for TExUS. The facility was successfully flown on the DLR missions TX-35 (1996) and TX-36 (1998) providing some spectacular features of plasma crystal behaviour under microgravity. In fact, these interesting results lead to the immediate demand for further systematic investigations with longer duration.

Already in February 2001 a series of plasma crystal experiments on the ISS could be started. The corresponding facility PK-3 Nefedov, developed by MPE, DLR and the Russian institute IHED of the Academy of Sciences, enabled the first scientific experiment onboard the ISS at all (cf. Fig. 5).

![TExUS module](image)

**Fig. 5.** TExUS module (left), and PK-3 Nefedov facility (right), the latter just having arrived the Russian compartment of the ISS in Feb. 2001, allowed unique investigations on plasma crystals under microgravity conditions.

The investigations on the ISS are still ongoing after more than four years of sequential facility operation. Without the investigations on TExUS the risk of failed experiments on the ISS would have been too high. In this respect, the TExUS facility both provided self-standing scientific investigations and was at the same time an important technology precursor of the ISS
hardware. The ISS facility as such could be developed in such a short time frame and operated in orbit successfully till now only due to the experiences gained with the TEXUS hardware.

6.2 Capillary channel flow

On TX-37 (2000) and TX-41 (2004) the stability of capillary driven fluid flow in channels, important for the future design of surface tension tanks in satellites, was successfully investigated. The third flight of the research facility is planned in November 2005. More specifically, the experiment cell and further major hardware items, to be flown as the second payload on this TEXUS-EML-1 mission, will later be adopted to the ISS facility CCF. The sounding rocket mission as such will utilize a new Brazilian rocket, to be launched from Kiruna (Sweden), and provide 6-7 minutes of microgravity. The planned series of long duration experiments onboard the ISS is expected to start in 2008. Due to the three sounding rocket missions performed in advance the development of the ISS flight hardware and its onboard operation is expected to benefit a lot.

6.3 Electromagnetic processing

First microgravity experiments of containerless processing by means of electromagnetic levitation of metallic melts were performed in 1994 (IML-2) and 1997 (MSL-1, MSL-1R) using the DLR facility TEMPUS on Spacelab flights. The results were convincing with respect to higher accuracy of thermophysical properties data of reactive metallic melts as well as to their measured solidification dynamics. Consequently, ESA and DLR decided to start a joint development of such a facility for the ISS. This facility called MSL-EML is expected to materialize in 2009 as part of the European COLUMBUS laboratory.

In the meantime, a joint ESA-DLR development was started for a TEXUS version of an electromagnetic levitator. This intermediate step turned out to be necessary to satisfy the urgent demand of the European metallurgical industry for thermophysical data of commercially relevant alloys. In fact, the 5-year joint ESA-EU research Project IMPRESS needs more accurate data of novel high-performance Ti-Al alloy melts to design improved turbine blades. Apparently, the sounding rocket facility will represent an updated successor of the Spacelab facility and a precursor of the ISS flight hardware at the same time. The first flight of the new facility will be on the mission TEXUS-EML-1 in November 2005.

6.4 Aerogel solidification furnace

A new furnace technology based on aerogels as mould material for processing metallic melts was utilized on the mission TX-39 (2001) for the first time. Such a transparent, highly porous material offers the advantages of non-wettability of metallic melts and the visual observation possibility of the melt. Subsequently, important process parameters (temperature gradient, solidification velocity) can be more exactly measured in-situ and time dependent by optical means.

On the mission TX-41 (2004) this furnace concept was extended by introducing a rotating magnetic field for the purpose of convection control in the melt. Because of their flawless operation and the very interesting results with respect to the achieved microstructures of Al-Si alloys, both ARTEx called furnaces will be re-flown on MAXUS-7 (2006) by ESA. Whether this promising furnace concept can be realized onboard the ISS, e.g. as an insert for the Microgravity Science Glovebox, remains still open and is mainly dependent on ESA's future budget.

7. SOUNDING ROCKET RESULTS

7.1 Solidification of immiscible alloys

Among the very first German experiments on sounding rockets (SPAR-1, TX-1, TX-2, etc.) monotectic alloys, which are immiscible on Earth in the liquid state and therefore of no practical interest for industrial applications, were chosen to achieve a homogenous microstructure. To overcome the sedimentation of elements with different densities, weightlessness seemed to be an ideal environment. Obviously, these first experiments failed with respect to alloy homogeneity and were disappointing at that point of time. More intensified investigations in the following years lead after all to a detailed understanding of the dominant physical mechanisms (Marangoni effect) causing separation of alloy phases in the melt. After a rather high number of dedicated rocket experiments the alloy homogeneity on a microscopic scale was finally demonstrated. These "lessons learned" nowadays allow to achieve such a microstructure under appropriate experimental conditions even in terrestrial laboratories. In fact, this progress opens up new perspectives for innovative casting technologies of lead free monotectic alloys that are applicable for bearings in the automobile industry.

7.2 Crystal growth of semiconductors

Looking back to the first crystal growth experiments on the German TX-6 mission (1982), it was convincingly demonstrated that dopant inhomogeneities in a Ge-crystal, so called striations due to time dependant convection in the melt, are avoidable by solidifying under microgravity. This early proof of the hypothesis lead worldwide to a lot of such experiments performed on Salyut, Skylab, MIR, FOTON, and a number of Spacelab and Spacehab flights in the following years.
On the German TX-36 (1998) mission the microscopic growth rate of doped Si and its correlation to temperature fluctuations could be measured in-situ and quantitatively for the first time. For that purpose, a mirror furnace was modified by a microscope and thermoelements attached to the immediate vicinity of the free melt zone. Finally, on the ESA mission MX-4 (2001) the experiments succeeded in controlling turbulent convective melt flows appearing in floating zone growth configurations. This result was achieved by applying tailored rotating magnetic fields for damping the time dependant melt flow. Consequently, even the avoidance of striations, otherwise permanently present in such floating zone experiments, could be achieved. Altogether, the sounding rocket results will be consequently applied for the thorough preparation of all planned investigations in this field on the ISS.

### 7.3 Simulated geophysical flows

An experiment on thermal convection under a central force field was implemented on the Russian sounding rocket VOLNA in June 1995. Using the dielectrophoretic effect, the central force field acting on an appropriate fluid in a spherical gap, is established by applying a high voltage between the inner and outer sphere. Thus, the action of gravity on fluid parts of planets (liquid core, atmosphere) can be simulated. Obviously, this type of experiments definitely requires weightlessness to turn off the unidirectional action of gravity in a terrestrial laboratory. The Thermal Convection Module TCM, weighing about 100 kg at a lengths of 1.2 m, contained three individual spherical cells with different gap widths. As illustrated in Fig. 6, the fluid flow between both spheres can be measured by optical means applying a tracer technique. During 20 minutes of microgravity, supercritical modes occurring at the onset of convection as a function of different aspect ratios were found. The results confirmed the theoretical and numerical predictions and stimulated future investigations. In fact, one of the first experiments on COLUMBUS will be performed in such a dedicated insert of the Fluid Science Lab. Thus, the geophysical flow of the Earth’s outer core consisting of molten Fe-alloys will be simulated.

#### 7.4 3-D plasma crystals

Soon after its discovery it turned out that establishing larger plasma crystals, i.e. ordered structures of micro-particles in a room temperature plasma, on Earth suffer from gravity leading to a compressed crystal lattice of a few layers in the vertical direction. Basically, the particle cloud remains restricted to the lower discharging electrode of the plasma chamber. On TX-35 (1996) the establishment of a larger 3-dimensional crystalline structure and its dynamics could be investigated in detail for the first time. Surprisingly, because more pronounced than originally expected, a big “void structure” in the centre of the particle cloud appeared. In the meantime, the void as such is explained by ion drag processes in the plasma and appropriate experimental conditions can be defined to strongly reduce this effect. Apparently, the TEXUS results became of utmost importance for the series of successful experiments performed on the ISS so far.

**CONCLUSIONS**

It has been shown that sounding rockets allowed a very early access to microgravity conditions for German scientists. Such missions provided a regular and reliable flight opportunity during three decades of operation. Especially, sounding rockets contributed to the implementation of the German Physical Sciences Programme in a large extend. Experiments on sounding rockets could mark some “first investigations” and achieved excellent results that were published in high ranking journals.

Currently, available ballistic rocket flights enable self-standing scientific experiments with a duration between 3 and 12 minutes at g-levels better than $10^4$ g. Therefore, the science requirements of a significant number of experiments can completely be satisfied by such flights now and in the future.

In several cases the experiment modules flown in the past on sounding rockets could be successfully “converted” into the design of ISS facilities. Because of the short time scales and lower costs associated with flight experiments, sounding rockets are still a very attractive flight opportunity. They are seen as very important for a successful implementation of the German Physical Sciences Programme. Microgravity experiments on sounding rocket will also be complementary to the increased ISS utilization in the upcoming years.