Comparison of ground based microgravity research facilities
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Matthias Raudonis and Lisa Wörner
German Aerospace Center for Quantum Technologies, DLR-QT, Ulm, Germany

Christoph Lotz and Ludger Overmeyer
Institute of Transport and Automation Technology,
Leibniz University Hannover, An der Universität 2, 30823 Garbsen, Germany

Sven Herrmann and Claus Lämmerzahl
Center of Applied Space Technology and Microgravity,
University Bremen, Am Fallturm 2, 28359 Bremen, Germany

Ernst M. Rasel
Institute of Quantum Optics, Leibniz University Hannover,
Welfengarten 1, 30167 Hannover, Germany

Christian Schubert and Wolfgang Ertmer
German Aerospace Center, Institute for Satellite Geodesy and Inertial Sensing, DLR-SI,
c/o Leibniz University Hannover, DLR-SI, Callinstr. 36, 30167 Hannover, Germany

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Abstract: Fundamental research is often bound by restrictions imposed by Earth's gravitational field. While experimenting in space allows for undisturbed experimentation, technological readiness, availability and accessibility present challenges for experimental operation. Ground based microgravity facilities can bridge the gap towards deployment in space. Besides being an accelerator for technology development, these allow fundamental and applied research with the additional benefit of being able to access and adjust the experiment in-between (experimental) runs.
This summary will outline available options and discuss their unique features.

I. INTRODUCTION

The gravitational pull of the Earth influences every experiment performed on ground. This impacts fundamental and applied research in various areas, ranging from life sciences, to studies of alloys and fundamental physics. For some of the research topics, counter measures can be employed to act against gravity, enabling experimentation [1–3]. However, most of these measures distort the potentials acting on the studied subject. With those additional forces, experimentation on small effects can be challenging or be rendered impossible.

To reduce the impact of gravity without introducing additional forces, experimentation in a freely falling systems is an option. A system freely falling in a gravitational potential will create a situation in which the subject of study falls with the observing system, thus appearing stationary. While the gravitational pull still acts on such an experiment, this is often referred to as 'microgravity environment', describing the acceleration of the object of study with respect to the detection systems.

The obvious choice for achieving a microgravity environment is to launch an experiment to space. But, operation in space is restricted by many factors, such as technological maturity, miniaturization, power consumption, limited sample size, and automatization. Additionally, programmatic limitations, such as monetary implications, platform restrictions, and availability of launch options, can prove to be difficult challenges to overcome.

Consequently, possibilities to achieve microgravity environments on Earth were sought out. Several facilities have been developed, which offer unique study opportunities to researchers as well as bridging the technology readiness gap for payloads. With these relying on free fall, the achievable microgravity time is limited, yielding the importance of space-based experimentation.

In this white paper we will focus on the following facilities:

1. Einstein-Elevator in Hannover, Germany
2. Drop Tower in Bremen, Germany
3. Parabolic Flights from Bordeaux, France
4. Sounding Rockets launched from Kiruna, Sweden.

Those will be individually described and their main capabilities compared for the conclusion of the paper. With this comparison, the achievable microgravity conditions, payload masses and volumes, repetition rates, and microgravity durations will be discussed.

Additional means, such as atomic fountains [4, 5], will not be discussed in this white paper, as those represent specific experiments as opposed to ground based microgravity facilities for usage by multiple experiments.

II. USE OF MICROGRAVITY ENVIRONMENTS

Fundamental and applied research profit from microgravity conditions. Microgravity conditions allow the study of effects masked by countermeasures, such as heating or magnetic levitation, enable more precise studies and the observation of small effects, and occurrence of effects not otherwise possible.
The latter comes especially into play when studying mixing of alloys [6, 7], combustion [8, 9], and fluid dynamics [10, 11]. The mixing of materials on ground is hugely dominated by buoyancy, electrostatic interaction, and molecular mass differences. With the removal of the gravitational pull, more uniform mixtures can be achieved, and flow phenomena studied [11–14]. This goes hand in hand with propellant management, which, in the absence of gravitational pull can pose a challenge to spacecraft operation.
With regards to spacecrafts, in addition to technological questions on propellant management, lifesciences and medical investigations are of high interest. Life science studies under microgravity include the growth of plants [15, 16] and the observation of animal behavior [17, 18], but also the study of human subjects [19, 20]. The latter is especially important to learn more about changes to the human physiology in space but also to cure illnesses and investigate motion sickness.
Microgravity further allows for the simulation of planet formation from dust particles [21]. Here, the study of aggregation processes aids understanding the emergence of proto-planets. From the observation of striations in jupiters rings, the necessity of observing dust particles not just in vacuum but also in ionized gases or plasmas arose. Complex plasmas under microgravity allow the study of particle aggregation, crystallization, flow transitions, wave phenomena, and lane formation [22–24]. Another area, where the removal of additional potentials enables studies of small effects are Bose-Einstein condensates and cold atom studies [25, 26]. Studies on cold and condensed atoms include effects, such as Casimir-Polder effects, the excitation of Feshbach resonances, the increase of momentum transfer in atom interferometry, and bubble formation. With such studies, inertial measurement units, missions in gravitational wave detection and Earth observation are now a possibility. At this time, a cold atom experiment is mounted to the international space station [27].

III. FACILITIES

A. Einstein-Elevator

The Einstein-Elevator at Leibniz University Hannover is a young facility for research under different gravitational conditions [28]. The beginning of its development was initiated in 2009 out of the former Cluster of Excellence QUEST. Through the very successful cooperation between the mechanical engineering and physics departments the worldwide unique facility, which was approved by the German Research Foundation (DFG) and financed by the federal and state governments, has been developed and built in-house. Research operations began in October 2019. The development of the next-generation drop tower facility was started with the vision of being able to perform the effects of quantum physics more efficiently, more cost effectively and with less expenditure of time. While developing the facility, other interesting topics have emerged, which also brought up the new research area at Leibniz University Hannover/ITA, dealing with production technologies under space conditions.

FIG. 1. Start position of the Einstein-Elevator for a vertical parabolic flight (credit: Leibniz University Hannover/Marie-Luise Kolb, licence: CC-BY 3.0 DE, [29]).

The Einstein-Elevator is the world's first next-generation drop tower system to go into operation. As an extension to classic drop towers, it features a novel guidance and drive concept [30, 31]. This opens up a number of new opportunities that are urgently needed by the scientific community. Statistical studies can be carried out with a repetition rate of 300 experimental runs per day in a three shift operation. In addition, the drives mounted along the travel path make it possible for the first time to simulate not only weightlessness but also other partial gravitational environments for an Earth-based facility. The larger dimensions and higher mass of the experiment also allow more elaborate setups. The experiments may be 1.7 m in diameter and 2.0 m in height and weigh up to 1,000 kg including the experiment carrier. An effective payload of about 550 kg is available.

The experiment carrier is located in a vacuum atmosphere for acoustic decoupling during free fall. Due to the frequent requirement of not wanting/being able to design the experiment hardware to be suitable for vacuum and to accommodate it in a normal atmosphere, the experiment carrier consists of an optional, pressure-tight shell, the experiment support structure and the

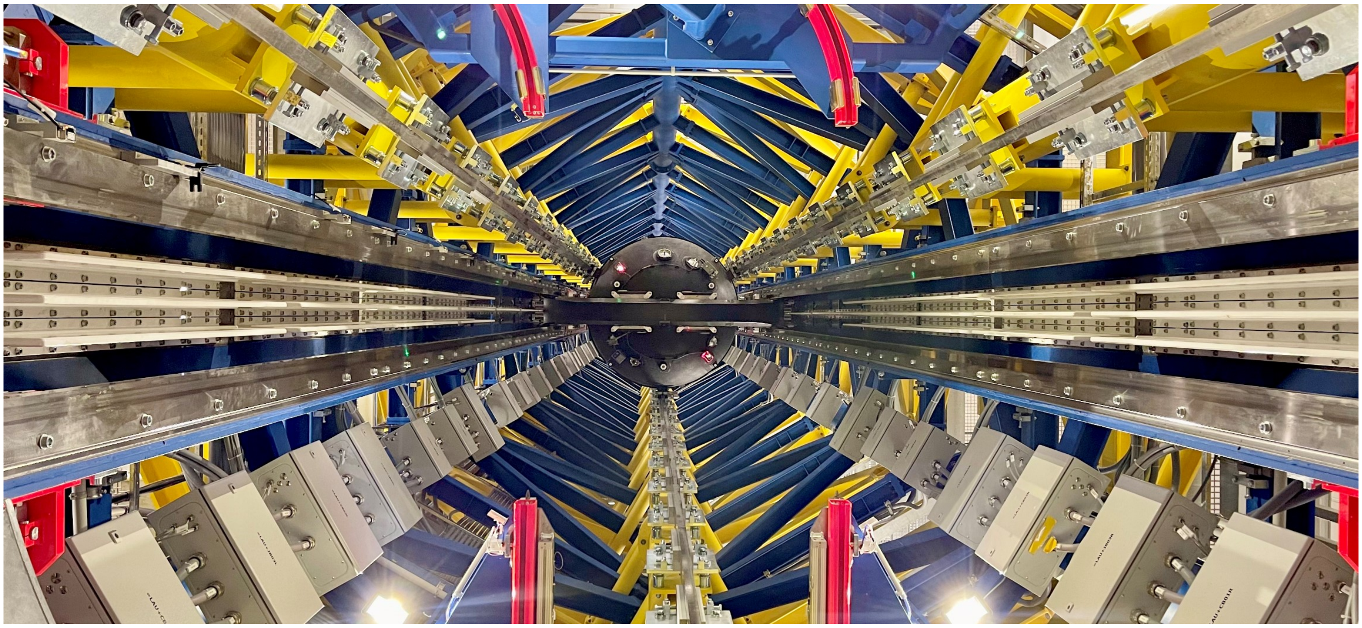

FIG. 2. Movement of the Einstein-Elevator during a vertical parabolic flight (credit: Leibniz University Hannover/Christoph Lotz, licence: CC-BY 3.0 DE, [29]).

carrier base. A wide range of equipment is available in the experiment carrier. An onboard computer records accelerations, temperatures, pressures, humidity and various other signals. In Addition high-speed cameras and surveillance cameras tested for this application can be used to observe the experiments. The telemetry and experiment data are transmitted continuously, even during the flight phase, using optical transceivers. A power supply, a vent line for vacuum pumps and a cooling water system with up to 1 kW are also available.

The experimental procedure includes the following steps:

- Integration of the experiment setup into the supporting structure of the experiment carrier
- Delivery of the fully assembled experiment to HITec
- Integration of the support structure into the carrier system and safety checks
- Insertion of the carrier into the gondola
- Preparation for the launch by closing the gondola and evacuating the interior space (see figure 1)
- Launch from lower position (4 s in µg) or upper position (2 s in µg)
- Vertical parabolic flight or drop (see figure 2)
- Safe deceleration
- Measurement data transfer
- Preparation for the next launch

During launch, the 2,700 kg of drive cart, traverse, and the gondola including the experiment are accelerated at 5 g by the 4.8 MW linear drive. A velocity of 20 m/s is thus achieved over the first 5 m. In contrast to classical drop tower systems, a release and catching mechanism is not required. The carrier stands unconnected on the bottom of the gondola and simply lifts off the ground shortly after reaching the final speed. Due to the controlled movement of the gondola and a balanced carrier, no horizontal movements occur that would cause the carrier to bump against the gondola walls. The distance between the gondola floor and the base of the experiment carrier is controlled to a defined distance of currently 50 mm during the complete flight phase. After the 20 m long upward and downward motion, the distance is reduced to zero again in a short time. The movement ends with an initiated joint deceleration. In addition to the catapult-like acceleration from the lower start position, it is also possible to start from the upper position if the experiment setup does not survive the 5 g of start acceleration or if the transition from 1 to 0 g is just to be simulated. However, in this case the free-fall duration is reduced to half the time (2 s).

The current research in the Einstein-Elevator is characterized by several topics. Further developments such as increasing the µg-quality through a novel experiment carrier system, and, on the horizon, achieving small defined residual accelerations are expanding the research possibilities and the properties of the system. In the field of space usable production technologies, the research focuses on laser material processing of different raw materials, like lunar regolith simulant material for

ISRU [32] or metal powder for a LMD process in zero gravity [33]. Furthermore, a large proportion of research is in the field of quantum physics. The search for dark energy and mass utilizes an atom interferometer. A significant rise in sensitivity of atom interferometers can be reached, when using them while free-falling with a compact low-energy wave packages, called Bose-Einstein condensates, in interaction with a specific test mass on macroscopic time scales of several seconds [34]. But also technology demonstration missions are executable. The first one was project Moonrise. Lunar regolith simulant material was successfully melted with a new developed space usable laser system [35, 36]. But also service operations of other topics like complex plasma research are feasible [37].

With the establishment of this next-generation facility, the following visions become achievable:

1. Explore quantum effects with high statistical goodness and highest quality. Develop new technologies. Rapidly implement engineering demonstrations of these technologies at low cost to underpin larger missions.
2. Establish new research fields such as research and development on production processes under space conditions. Enabling building spare parts in space or habitats on other planets.
3. Make research under space conditions available to the broader research community through efficient, cost-effective, and rapid experimentation.

Next-generation drop towers such as the Einstein-Elevator enable the scientific community to gain tremendous advantages in the execution of their experiments.

B. Drop Tower

The Bremen drop tower has been operating continuously since 1990 and has so far provided its services to researchers from 42 countries, operated more than 160 different experimental setups from research fields as diverse as astrophysics, biology, fundamental physics, fluid dynamics including cryogenics or material science. It serves as a platform for stand-alone microgravity research but also for verification and testing of key components and mechanisms in payloads or hardware for satellites and other orbital platforms. Examples are the QUANTUS project with the first creation of a Bose-Einstein condensate as well as matter wave interferometry in microgravity [25, 38], verification of the T-SAGE accelerometer of the MICROSCOPE mission [39] or verification of the asteroid impact sampling device of the Hayabusa-2 space probe [40].

The tower stands at a total height of 146 m with an internal drop tube, which is decoupled from the outside structure and measures 122 m in height and 3.5 m in diameter. The available free fall time per drop is 4.7 s. At the bottom of the tube the experiment capsules are captured and decelerated inside a container filled with styrofoam pellets. This exposes the experiment to an average deceleration of 25 g in 200 ms with a peak just below 50 g. In order to eliminate air friction during free fall and reduce residual accelerations to a level of few parts of $10^{-6}\,g$, the drop tube is evacuated to 0.1 mbar in about 90 minutes prior to the drop. After each drop, the tube is vented again for about 30 minutes to allow for recovery of the experiment. This procedure allows for typically three successive drops per day.

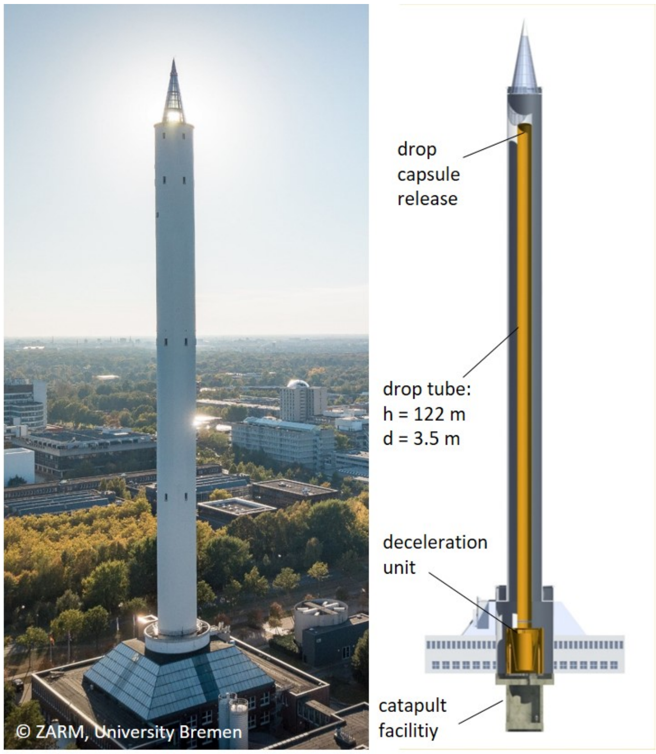

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FIG. 3. The drop tower at ZARM, University Bremen.

Typical experiment campaigns extend over days or weeks, with each experiment being integrated inside a drop capsule prior to a campaign, with assistance from the drop tower engineering team. In standard configuration the drop capsules allow for 500 kg total mass, which leaves ca. 264 kg for the payload at a maximum payload height of 1.7 m and 0.6 m in diameter. In drop mode the limitation on height and mass is not a strict limit and customized capsules with payloads exceeding 2.0 m with or to 680 kg have been operated as well. The standard configuration of the capsules is to provide an on-board computer for collecting house keeping data, a battery platform with 24 Ah and an interface for electrical connections to buffer the battery platform (24 V, 10 A) as well as for cooling media, allowing for 2.6 kW of cooling power.

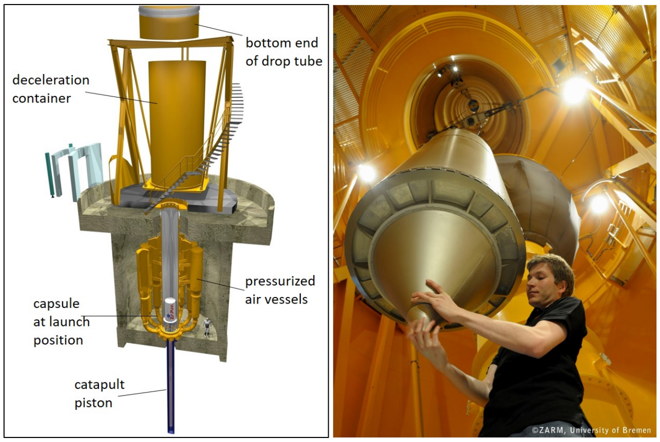

FIG. 4. Left: detail of the catapult system and deceleration chamber at the bottom of the tower. Right: Drop preparation. A cone is attached to the bottom of the capsules in order to reduce the shock upon impact into the deceleration container.

a. Drop Tower with catapult:
Since 2004, the drop tower also incorporates a catapult system, that allows to extend the free fall time up to 9.3 s. This facility can launch catapult capsules of up to 400 kg (161 kg payload) and 0.95 m payload height. The catapult uses a combination of pneumatics and hydraulics to accelerate the experiment capsule placed on a piston at 18 g in about 280 ms (peak acceleration is 30 g). The combination of 9.3 s of free fall at micro-g levels with low cost and easy accessibility is a unique feature of this facility.

Only recently drop tower and catapult have been augmented by a new facility GTB-Pro (Gravi Tower Bremen Prototype). This system is currently in the final comissioning phase and will start providing its services during the first quarter of 2022. GTB-Pro is integrated just outside the deceleration chamber and within the confinement of the integration hall ceiling which allows for 14.9 m height. It offers increased repetition rate with up to 20 experiment runs per hour and a free fall time of 2.5 s for experiments integrated in a catapult capsule of up to 500 kg total mass. The system applies drag shields that are actively accelerated with up to 5 g by a hydraulic drive and rail guided, thus avoiding the need for vacuum conditions. A fast and reliable decoupling and recoupling of the experiment is made possible by a novel Release-Caging Mechanism (RCM) developed at ZARM [41] in order to provide lowest microgravity levels similar as for regular catapult operation. The GTB-Pro is of particular interest for experiments that do not need free fall times > 2.5 s but require hundreds of repititions. Compatibility and proximity to the drop tower catapult system also allows to do fast and extensive parameter scans in microgravity, as far as the 2.5 s of free fall allow, in preparation of single long shots on the catapult with the same experiment on the same day.

C. Parabolic Flight

Parabolic flights employ airplanes to generate microgravity conditions. For this a maneuver of ascend followed by the ignition into a parabolic trajectory and a pull out into normal flight configuration is performed. The phases of the flight are depicted on the novespace homepage [42]. From the picture it can be seen that the plane is first subjected to a 1.8 g hyper-g phase during which the airplane ascends. It is then injected into the parabola, lasting for 22 seconds. During this time the airplane falls freely in the gravitational potential leading to the experience of microgravity inside of the plane. Afterwards, the airplaine is pulled out of the parabola before it is back in nominal flight configuration. During a flight 31 parabolas are flown.

Throughout the maneuver the plane is controlled by three pilots, to allow for smooth transitions, low roll, and a straight trajectory. With this control, microgravity stability is in the range of $\pm 0.002\,g$ [42]. To achieve the calmest environment, the scientific experiments are mounted to the mid-section of the plane, where a total of $100\,m^2$ [42] of area is available. After completion of the flight, the full vibrational spectrum, as recorded by the plane, is handed to the researchers to compare to their experimental data.
The total mass of the scientific instruments is $4.000\,kg$ [42]. Usually experiments are expected to have a mass around $100\,kg$ and are required to state their center of mass. With that information, the experiments are distributed inside the cabin. Large experiments, which take up the entire space are not unheard of and possible for the plane to accommodate.
A usual flight campaign lasts for two weeks. During the first week the researchers and their experiments arrive on site. They are given some time to prepare the experiments and load them into the plane. During this time, the safety instructions are provided to the researchers and human subjects. On three following days, daily flights are performed, after which the experiments are removed from the plane.
Parabolic flights, offer several advantages over the other ground based facilities:

- The researchers can execute the experiments themselves and manipulate the system in real time.
- Human test subjects are possible, allowing to study a wide variety of subjects with high statistics.
- While the plane experiences 1.8 g of hypergravity, this is much less compared to the impact of, for example a sounding rocked landing.
- The plane supplies power to the experiments during flight.
- Large and heavy experiment can be accommodated.

The main disadvantages of the parabolic flights are the high level of residual vibrations caused by the people on board, the air surrounding the plane, and the flight parameter. Other disadvantages are the limited amount of flights available to researchers, especially with respect to the Einstein-Elevator, and the additional safety regulations that have to be observed.

D. Sounding Rockets

Rockets to LEO use most of their propulsion capability Δv to reach orbital velocity - much more than to reach the orbit height potential.

$$\Delta v = v_\mathrm{e} \ln \frac{m_0}{m_f}$$

FIG. 5. Tsiolkovsky rocket equation where v_e is the exhaust velocity, m_0 is the initial rocket wet mass and m_f is the final mass of the rocket after propulsion. For multistage rockets, the equation must be computed for each stage separately.

According to the Tsiolkovsky rocket equation (figure 5), the rocket wet mass scales exponentially with increased Δv requirements. Because of the high mass required for orbit, the size, energy and launch cost of orbiting rockets is high.
Sounding rockets reach space altitudes, but do not accelerate to orbital velocities for orbital insertion. This dramatically decreases size, energy and launch cost per payload mass.
After launch, the rockets follow a steep parabolic trajectory. Then, the second stage burns out, separates and de-spin systems are activated to stabilize the payload. As the rocket leaves the atmosphere on a sub-orbital trajectory ("free fall"), the lack of atmospheric drag force creates the desired microgravity environment. At the end of the microgravity period, a mild atmospheric reentry happens with the help of heatshield and parachutes. The payload is then retrieved by helicopter with the help of a beacon.

The European Space and Sounding Rocket Range (ESRANGE) is next to Kiruna in northern Sweden, 150 km north of the polar circle. ESA has launched sounding rockets for over 30 years from this site. The remoteness of the site allows unguided launches with a large uninhabited recovery area of $5600\,km^2$. [43] A unique feature of ESRANGE is its pyramid-shaped launch tower, which allows launch preparations without the interference of the arctic climate. ESRANGE also features ground support facilities to monitor and control every aspect of the launch. The proximity to Kiruna allows relatively good accessibility with roads. Kiruna has a train connection and an international airport.

"Mobile Raketenbasis" (ger. mobile rocket base - MORABA), is a department of DLR. They provide sounding rocket research platforms for atmospheric, hypersonic and microgravity research. [44]

Parts of its portfolio consists of military surface-to-air motors, which were decommissioned and demilitarized, allowing a competitive price. The rockets range starts from the "Improved Orion" which can carry light payloads up to $\approx 80\,kg$ for short duration microgravity research. [45] The MAXUS and TEXUS rockets are based of the VSB-30 platform, which allows long duration microgravity with medium payloads. A graphical overview over the different types of rockets can be found here: [44]

The reachable apogee (furthest point from earth) depends on the available energy of the rocket motor, but mostly the ratio $\frac{m_0}{m_f}$ of the initial mass m_0, containing the fuel and the final mass m_f. (equation 5) The final mass consists ideally only of the payload and recovery systems. Therefore, the reachable apogee for a rocket type is highly dependent on the payload mass. A graphical representation of that dependency can be found in [45].

The duration of the microgravity time is the time the rocket spends above the atmosphere. Comparable with the Drop Tower with catapult, half of the time above the atmosphere is spent ascending to the apogee and the other half descending to the edge of the atmosphere. On a suborbital steep parabolic trajectory, the total microgravity time is dependent on the reachable apogee [48].

The two stage MORABA large sounding rocket VS-50 is currently under development in Phase D. Due to the increase of propulsion capability, the rocket will reach payload masses of up to 1,000 kg or altitudes of 2,700 km, which equates to 1,800 s of microgravity. [45, 47]

Sounding Rockets offer one main advantage over the other ground based facilities: The microgravity time of several minutes with relatively high stability.

With this advantage, compromises have to be made with regards to mission design:

- The mission cost is comparably very high per launch. However, experiments can be recovered and reused.
- The full impact area at ESRANGE is only available during winter.
- The payload weight and size constraints. Additional weight limits the microgravity time.
- During ascent and landing, the rocket endures high accelerations of several g which could damage the payload.

IV. COMPARISON

In table I, the repetition rates and available flight masses and areas are summarized. From the table it is visible, that the choice of the ground based microgravity facility depends strongly on the requirements for the

TABLE I. Comparison of μg facilities.

Facility	Free fall time	Repetition rate	Stability	Payload Size
Einstein-Elevator	4 s (drop: 2 s)	300/24 h	$\approx 10^{-6}\,g$	d = 1.7 m, h = 2.0 m, m = 1000 kg
Drop Tower	4.7 s	3 per day	$\approx 10^{-6}\,g$	d = 0.6 , h = 1.7 m, m = 264 kg
Drop Tower w/ catapult	9.3 s	3 per day	$\approx 10^{-6}\,g$	d = 0.6 , h = 0.95 m, m = 161 kg
GTB-Pro	2.5 s	20/h	$\approx 10^{-6}\,g$	d = 0.6 , h = 0.95 m, m = 261 kg
Parabolic Flight	20 s	31 flights per day	$\approx 0,02\,g$	avail. area = 100m^2, m = 4000 kg
Sounding Rockets	up to 13 min	1 flight per day	$\leq 10^{-4}\,g$	$d \leq 640mm$, $m \leq 800kg$

TABLE II. Brief comparison of MORABA rocket models example configurations including TEXUS, MAXUS [46] and VSB-50 [45, 47] sounding rockets.

	TEXUS VSB-30	MAXUS Castor 4B	VSB-50
P/L diameter	438 mm	640 mm	1500 mm
sci. PL mass	270 kg	500 kg	1000 kg
apogee	250 km	750 km	2600 km
microgravity	400 s	730 s	1800 s
stability	$10^{-4}g$	$10^{-4}g$	

experiments. For instance, if a very long microgravity time is preferable over large statistics, a sounding rocket is probably the best option. In a case where repetition rates and statistics are the dominant requirement, the Einstein-Elevator is a better choice.

The parabolic flights alone allow for the study of human subjects with large variety and high statistics. While long term effects can only be studied on the international space station, parabolic flights are an important option for life sciences and medical studies.

All of the facilities excel in recovering the experimental setup with the sounding rockets, where the payload has to be recovered from after the parachute landing, proving to be the most complicated and challenging to the payloads design.

V. CONCLUSION

Several different ground based microgravity facilities have been discussed. With these facilities both fundamental research and technology development can be executed, creating a important bridge between laboratory and space-based experiments. With financial budgets and direct accessibility for the researchers, the ground based facilities are an interesting solution to performing experiments under microgravity, testing hypothesis and evolving technologies.

As the experimental and technological requirements are different, in the end of the paper, a comparison between the facilities has been outlined. This comparison is based on the facilities discussed in the paper. With other facilities, for instance with varying free fall times, the values can be changed. However, already from the comparison it can be judged, that the leader of an experiment has to carefully consider their requirements and then choose the appropriate facility.

Regardless of the individual choice or preference, all of the mentioned facilities are well booked, demonstrating the necessity for the accessibility of microgravity environments. With that note, the authors want to encourage further facilities, allowing for easier access for more experiments and future advancements.

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