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Facilities to Alter Weight

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Drop Towers

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6.1 Introduction

While the utilization of space-based or flight-based facilities can provide longer-duration test times than can be provided by Earth-based facilities, access to these facilities comes with an associated significant increase in cost and often an associated decrease in availability. These problems are somewhat mitigated by the use of ground-based facilities that are often able to provide very good levels of reduced gravity coupled with low cost (per test) and significantly better access (than flight-based or space-based facilities). This section provides a brief overview of ground-based facilities that are able to provide periods of reduced gravity for the testing of various phenomena in many diverse disciplines. Described in detail are the different types of facilities available and the principle used in these facilities to produce low-gravity conditions. A short description of the various discipline areas currently utilizing these ground-based facilities is included for completeness.

Ground-based methods permit (with low cost, good access, and high test rate) the conduct of complex experiments. Experiments useful in many diverse discipline areas have been, and will continue to be, conducted in the reduced gravity environment produced inside a drop tower. These discipline areas include materials, fluids, astrophysics, phase transitions, combustion, fire safety, fundamental physics, biology and life sciences, heat transfer, mechanics, and technology development.

6.2 Drop Tower Technologies

The first drop test performed, attributed to Galileo (in the late 1500s), supposedly occurred from the Leaning Tower of Pisa to demonstrate that objects fall, independent of their mass, at the same acceleration in the Earth's gravitational field. That is, an object in free fall is essentially in zero gravity. A problem for a falling object in a fluid medium such as air, however, is the development of aerodynamic drag, which results in the slowing down of the falling object, thus reducing (or eliminating) the reduced gravity conditions as the object approaches its terminal velocity. A ground-based facility that is providing reduced gravity conditions must, in some fashion, reduce or eliminate the presence of Earth's gravity and the effects of this body force on the phenomena being investigated while, at the same time, eliminating the detrimental effects of aerodynamic drag. This is accomplished by accelerating the experiment, at 1 g, in a vector parallel to Earth's gravity relative to the Earth's centered frame of reference. Matching the Earth's acceleration essentially produces a free fall environment within which the experiment is in a zero-gravity condition in the freely falling reference frame. The precision to which the experiment's acceleration is matched to Earth's gravity level dictates the quality of the reduced gravity that is obtained.

The drag produced, and its effects, on an object moving through a fluid, has been well studied and characterized over many years, and this work is well documented in publications due to its relevance to many disciplines. Drag coefficients have been developed and allow researchers to predict and plan for the effects of the aerodynamic drag, as required, as a function of an object's geometry and the flow conditions present.

There are several options available to eliminate the aerodynamic drag, and the method selected often dictates (constrains) many of the other operational aspects of the drop tower. The options available to reduce or eliminate the aerodynamic drag include a) dropping in a vacuum, b) dropping inside a drag shield, c) guided motion where the falling object's acceleration is matched to Earth's gravity, and certain other d) enhanced technologies (free flyers, catapults, etc.). These various methods and their specific attributes are discussed below.

6.3 Vacuum (or Drop) Tubes

Some of the earliest vacuum (or drop) tubes were used to produce commercial outcomes in the late eighteenth century for the production of high-quality spherical lead shot. Within a drop tube, the effects of aerodynamic drag are typically removed by evacuating the entire tube. This evacuation eliminates the possibility of any air drag developing on the test sample, thus allowing it to continually accelerate at 1 g during the drop. While the sample or experimental platform is in free fall, it is weightless and the effects of gravity on the phenomena being investigated can then be determined. Some drop tubes are relatively small (<1 m) in diameter and drop the test sample itself (without an experimental package), while other drop tubes are relatively big (several meters in diameter) and able to drop very large, complex experimental platforms which, however, may require a long pretest time to remove the atmosphere (air) present so that the aerodynamic drag is eliminated.

The duration of the free fall provided within a specific drop tube is directly related to the initial height of the drop through Newton's law as follows:

$$x = x_0 + v_0 t + \frac{1}{2} a t^2 \tag{6.1}$$

where t is the time of free fall, x is the distance travelled, a is the acceleration (in our case, a is the Earth's acceleration of g), and x_0 and v_0 are the initial height and velocity (v_0 is typically zero). This relation shows why all ground-based drop facilities (including vacuum tubes) are only designed to provide short durations (2–10 s) of reduced gravity. For free fall with zero initial velocity, the free fall duration is given by

$$t = \sqrt{\frac{2h}{g}} \tag{6.2}$$

where $h = x - x_0$ is the total distance dropped. This shows that doubling the height increases the free fall time by a factor of $\sqrt{2}$ only. In a catapult mode, where the experiment is initially launched upward, the free fall time doubles.

6.4 Experiment Inside Capsule (Drag Shield)

Another way to eliminate or reduce the aerodynamic drag on an object, and the operational principle some ground-based facilities are based upon, is the utilization of a "drag shield." In this configuration, shown schematically in Figure 6.1, the experimental platform is placed in a capsule or drag shield. During a test, the capsule experiences the aerodynamic drag developed as it drops through the air; however, the experiment that is inside

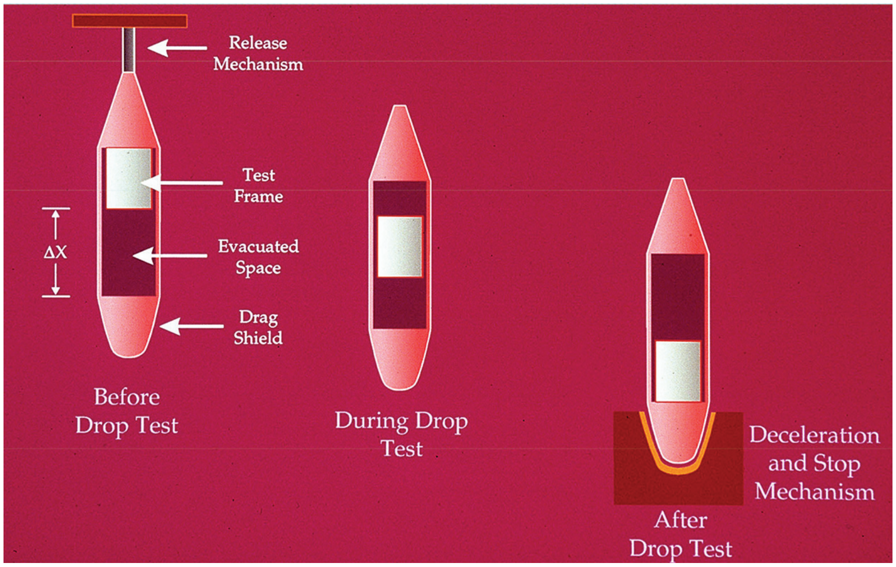

Figure 6.1 Use of drag shield to eliminate aerodynamic drag on experiment to produce reduced gravity conditions.

the capsule does not experience significant air resistance since it is only falling a short distance relative to the capsule. In this way, the aerodynamic drag on the capsule does not significantly affect the experimental platform, essentially in free fall, inside the capsule over the course of the test.

It is now interesting to know how large the initial spacing ΔX between the capsule and the bottom of the experiment platform (as shown in Figure 6.1) has to be for a free fall time of several seconds. For that, we calculate the difference of the perfect free fall given by Equation (6.1) and a fall within air where the drag shield experiences Stokes and Newton air friction. The equation of motion for this is as follows:

$$m\dot{v} = mg - \beta v - kv^2, \tag{6.3}$$

where β is the Stokes air friction coefficient and k is the Newton air friction coefficient. This equation can be solved exactly and gives

$$v(t) = -\frac{\beta}{2k} + \sqrt{\frac{\bar{g}m}{k}} \tanh\left(\sqrt{\frac{\bar{g}k}{m}}t + \tanh^{-1}\frac{\beta}{2\sqrt{k\bar{g}m}}\right) \tag{6.4}$$

where $\bar{g} := g\left(1 + \frac{\beta^2}{4kmg}\right)$. This is the velocity of the drag shield as function of time. The terminal velocity is $v_\infty := \lim_{t\to\infty} v(t) = -\frac{\beta}{2k} + \sqrt{\frac{\bar{g}m}{k}}$ from which we recover the well-known cases for $\beta \to 0$ and $k \to 0$. For the position of the drag shield, we then obtain

$$x(t) = -\frac{\beta}{2k}t + \frac{m}{k}\ln\left(\sqrt{1 - \frac{\beta^2}{4k\bar{g}m}}\cosh\left(\frac{\bar{g}k}{m}t + \tanh^{-1}\frac{\beta}{2\sqrt{k\bar{g}m}}\right)\right) \tag{6.5}$$

The spacing between the drag shield and the free flyer (test frame) then is $\Delta x(t) = \frac{1}{2}gt^2 - x(t)$. An expansion for short times gives

$$\Delta x(t) = \frac{\beta g}{6m}t^3 + \frac{g^2 k}{12m}\left(1 - \frac{\beta^2}{2gkm}\right)t^4 + \sigma(t^5). \tag{6.6}$$

The maximum possible time of flight is given by $\Delta x(t_{\max}) = \Delta X$. The result depends on the coefficients β and k which also depend on the air viscosity and the geometry of the drag shield. According to this result, most ground-based drop facilities are only designed to provide short durations of reduced gravity since the spacing required for long drops becomes much larger as drop time increases.

6.5 Drop Tower Systems

As drop towers permit entire experimental systems/platforms to be dropped, they can vary considerably in their size ranging from small drop corridors (of about 1 m diameter) to very large dimensions (of several meters in diameter). A drop tower facility, in general, will consist of (a) a drop corridor within which the experiment resides during the period of reduced gravity, (b) experimental system(s) mounted on an experimental rack unique to the phenomena being investigated and the facility the test is to be conducted in, (c) some method to produce reduced gravity conditions for the experimental platform, (d) a lifting mechanism for the experimental platform, (e) a holding and release mechanism for the experimental platform, (f) a deceleration device to stop the experimental package at the conclusion of a test, and (g) space to prepare experiments and interact with/provide access to the drop corridor.

The drop corridor is the vertical extent within which the experiment is dropped to obtain free fall conditions. Access to the drop corridor is necessary at some location to allow the experiment to be inserted and removed, as required, and this often is associated with a laboratory area for researchers to prepare their experiments. Typically, access to the experiment within the drop corridor is provided at the start of the test. In an evacuated system such as in a drop tube, special considerations are often necessary to ensure the vacuum level in the drop corridor is not lost as the experimental system is moved into the drop corridor. The experimental system is used to contain all aspects of the test being conducted. As the experiments are typically in free fall within the drop corridor, all aspects (power, data and image acquisition, device controllers, switches, etc.) of the testing are performed remotely after the test is initiated (dropped). In the case of a system utilizing a drag shield, the experiment must be loaded into the drag shield and the resulting package readied for (and recovered from) the drop corridor as a single item. If required, a lifting mechanism is utilized for raising (pretest) or recovering (post-test) the experiment and/or experiment and drag shield. At the initiation of a test, the experiment (and drag shield, if used) must be held and released, as required, consistent with the facility requirements for test initiation. One of the most critical things during test initiation is the minimization of any unwanted vibrations (g-jitter) that may be imparted to the experiment as this unwanted acceleration can, depending upon the experiment, detrimentally affect the results. At the conclusion of a drop test, a deceleration device is essential to bring the experimental system (and drag shield, if used) to a controlled stop in a safe fashion.

6.5.1 Guided Motion

An alternative to the basic drop tower configuration described above is provided by a "guided motion" drop system. In a guided motion drop system, there is no need for a drag shield as the experiment is contained in a capsule that is then propelled downward at an acceleration of 1 g. The guided motion of the capsule is typically obtained by rail guides and/or levitated drive devices (similar to high-speed trains). By matching the Earth's gravitational acceleration, the capsule is essentially in free fall and in a 0 g environment. The matching of the capsules' acceleration to Earth's gravity vector is normally accomplished by having the capsule move along a predefined velocity profile (easily derived through the use of Equation 6.1). Since the velocity (and, therefore, the associated distance travelled) increases significantly with time, these facilities are typically limited to between 5 and 10 s of test time.

6.6 Enhanced Technologies

Several technologies are used to further increase either the duration (time) or quality (level of reduced gravity) of the test environment within the systems described above and are presented here.

6.6.1 Free Flyer System

Precise experiments often require an enhanced environment which sometimes exceeds the given quality level of reduced gravity in an evacuated drop tube or in a drag shield. In general, the quality of reduced gravity depends on the residual air pressure present. These drop systems will typically have several hundreds up to a few thousands of cubic meters of air to evacuate. From an operational point of view, since the vacuum pumps utilized have limited pump speeds, there will often remain a pressure of a few mbar in the drop corridor. For the drop tower Bremen, there is about 0.1 mbar present that allows excellent microgravity conditions of about 10^{-6} g to be produced. In order to further reduce the gravity level for special precision experiments, a free flyer system is applied [1]. The concept of the free flyer is based on the utilization of a drag-shielded experiment as previously described which is dropped inside an evacuated drop tube. In this application, the free flyer system effectively minimizes residual disturbances being caused by the low-level aerodynamic drag still present. At the drop tower Bremen, experiments utilizing the free flyer system can achieve reduced gravity conditions of about 10^{-7} g.

6.6.2 Catapult System

An increase in the time of reduced gravity available in a drop tower can obviously be obtained by simply building a higher drop tower or longer drop shaft. Due to the fact that, however, the time of reduced gravity available is a function of the distance dropped to the ½ power (Equation 6.2), construction of drop towers or drop shafts does not seem to be very economical after reaching a certain drop distance. A less utilized approach that essentially doubles the test time for a given drop distance is to catapult the experiment upward from the bottom of the drop corridor to make both the way up and the way down available (this is an especially attractive option in an existing drop facility since no further height is required). Although the experiment is initially accelerated after its detachment from the acceleration unit (i.e., the catapult), it performs a free fall in a vertical parabola (comparable to parabolic flights). Either in an evacuated drop tube or in a drag shield configuration, a catapulted experiment becomes a free-falling body and is weightless.

Accelerating an experiment capsule carrying hundreds of kilograms of payload requires a powerful drive coupled with precise control and handling of the capsule movement which is essential during the acceleration phase and to ensure exact capsule alignment during the flight phase within the confines of the drop corridor. At the moment, the drop tower Bremen is the only ground-based facility with a catapult system [2]. This world unique catapult system is installed in a chamber below the basement and utilizes a combined hydraulic–pneumatic drive to accelerate an experimental capsule (with a total mass of over 400 kg) to the top of the evacuated drop tube on a vertical parabola. The pressure difference between the vacuum level present inside the drop tube and the compressed air below the catapult piston (stored in pressurized air tanks) is utilized as the driving force of the catapult system. The acceleration level of the catapult (with up to 30 g's achieved within about 300 ms) is adjustable by a servo-hydraulic braking system that provides smooth control of both the overall piston velocity and the final transition of the experiment to microgravity at release. Typically, an experimental capsule will leave the catapult system with a lift-off speed of the about 48 m/s at 10^{-6} g with minimal vibration from the catapult.

6.6.3 Next-Generation Drop Towers

Drop facilities represent an important economic alternative with straightforward and permanent access to weightlessness on Earth in comparison with the other possible flight opportunities. In recent years, numerous demands of higher repetition rates for experiments under weightlessness have been observed at the available ground-based facilities. The reasons are, on the one hand, that current experiments become more and more complex and they require, therefore, higher repetition rates to generate the specific number of experiment parameters for their success. On the other hand, experiments need reliable statistics in their experimental results which have been achieved so far. Both scientific aspects and additionally the continuous technological progress in the present experiment developments (i.e., fully autonomous computer operations) lead to a magnitude of demand that exceeds the given capabilities afforded by existing drop facilities. The limiting factors of achieving higher repetition rates and thus laboratory-closed conditions at the present drop facilities include the time it takes to evacuate the drop tube and experiment capsule recovery and preparation for the next drop. At the drop tower Bremen, a second drop facility is currently planned which offers repetition rates of over 100 experiments per day in a semi-continuous laboratory operation. This next-generation drop tower system, the so-called GraviTower Bremen, combines the technological benefits of the catapult system of the drop tower Bremen with a guided electromagnetic linear drive. The new facility concept is based on the operation of a commercial elevator in which the distance between passenger (i.e., the experimental payload a free flyer) and cabin walls (drag shield) is actively regulated. After each initial acceleration, and subsequent detachment, the experimental payload becomes a free-flying body and is weightless. In order to smoothly accelerate and decelerate an experimental payload of several hundred kilograms on a vertical parabola in such a guided catapult system, it is essential to work with a both powerful and precisely controllable drive. An electromagnetic linear drive commonly utilized in roller coasters represents a commercially available and well-tested solution for the semi-continuous experiment operation. As currently planned, the GraviTower Bremen will have a height of about 70 m and will provide fall durations of 6 s at microgravity conditions. The different free fall durations will depend on the selectable acceleration/deceleration drive mode with a range available between 1.5 and 4.0 g. Only very low initial experiment disturbances are expected during the acceleration phase. The accuracy in power and control of the applied electromagnetic linear drive allows also a novel operation mode with a fixed "free flyer." In this case, experiments under partial gravity (at gravity levels from 0.1 to 0.4 g with an expected accuracy of 10^{-2} g) can be conducted. The duration of partial gravity available at the GraviTower Bremen ranges from 5.5 to 7.8 s and depends on both the partial g-level and drive mode selected. Finally, the dimensions of the GraviTower's free flyer are planned to handle much larger volume and mass than in other existing facilities.

6.6.3.1 Ground-based facility's typical operational parameters

In the characterization of a ground-based facility, four factors are most significant: test time, magnitude of reduced gravity (quality), size of experiment that can be accommodated, and cost. Other parameters are sometimes considered such as facility location, deceleration experienced at test conclusion, and technical assistance available. These characteristics are function of the facility being considered and the methodology it uses to produce the reduced gravity. Examples of these characteristics are provided and contrasted in Table 6.1.

Table 6.1 Characteristics of a large and a small ground-based reduced gravity

Facility	Location	Test Time (s)	g-Level (g's)	Approximate Size of Experiment	Approximate Cost	Deceleration Level at Test Conclusion
ZARM	Bremen, Germany	4.7 or 9.3 (with catapult)	$10^{-6}/10^{-7}$ (with free flyer)	Cyl.: up to 0.8 m dia., up to 1.7 m long, about 300 kg (different exp. capsules)	Varies	Up to 50 g (typical 40 g)
NASA	Cleveland, USA	5.2	10^{-6}	Cyl.: up to 1 m dia., up to 1.6 m high, up to 455 kg (incl. drop vehicle)	Varies	up to 65 g (mean 35 g)
NML	Beijing, China	3.6	$10^{-3}/10^{-5}$ (with free flyer)	Varies	Varies	15 g
QUT	Brisbane, Australia	2.0	10^{-4}–10^{-6}	Cyl.: 0.9 m dia × 1.5 m long	€400–€600	15–20 g's for ~0.25 s

6.7 Research in Ground-Based Reduced Gravity Facilities

There are many scientific discipline areas that currently use ground-based facilities to produce reduced gravity test conditions to study relevant phenomena. A short description of some of the work being conducted is presented.

6.7.1 Cold Atoms

Quantum objects show interference: If a beam of quantum objects is split coherently and the two beams are moving along different paths, then after recombination of both beams, interference will occur. The interference pattern is influenced by external influences like acceleration or rotation of the whole interferometer or by the influence of other external forces. The important issue is that the effect on the interference scales with the square of the time the atoms move within the interferometer. While on ground, the atoms will fall down the table within a tenth of a second, we can increase the time if the interferometer will fall together with the atoms. In a free fall environment, interferometers become much more sensitive. Since after a few seconds, the coherence of the two beams disappears due to imperfect isolation against disturbances, drop towers are currently ideal facilities to perform such experiments [3, 4]. A future goal of this ground-based work is to bring cold atoms to space, that is, on the ISS or on dedicated spacecraft. This work supports fundamental physics experiments such as quantum tests of the equivalence principle, tests of the linearity of quantum mechanics, or practical applications such as geodesy and Earth sciences.

6.7.2 Combustion

Combustion experiments in many diverse areas are being studied. Some studies are aiming at a thorough investigation of the self-ignition of droplets of different types of fuel, including modern biofuel of the second generation [5]. These investigations form the foundations of the understanding of the physical processes underlying spray ignition needed for efficient and ecologically compatible combustion. The unique heterogeneous (liquid phase) burning of bulk metallic materials in oxygen-enriched atmospheres is also being studied with specific applications to fire safety and fundamental combustion science [6, 7]. For these experiments, weightlessness is of big advantage because (i) convection then does not occur, (ii) the system is simplified due to the spherical symmetry of the liquid-phase droplets, and (iii) one can study larger droplets which often permit a more detailed observation of the processes being studied. One main result from the obtained data is input to assist the development of a computer simulation for the detailed study of the complete spray ignition process. This has a big impact on the construction of energetically efficient and ecologically compatible engines.

6.7.3 Fluid Mechanics/Dynamics

It is obvious that fluids behave differently according to whether gravity is present or not. One effect is related to the surface tension which makes it possible, in the absence of gravity, for large liquid balls to be formed. Another effect is related to capillarity: For very weak gravity, the effect of adhesion of water at surfaces becomes dominant with the effect that a fluid will move along surfaces. A particular topic being investigated is the behavior of free surfaces [8]. Such an effect can be used for propellant management devices or life support systems in satellites.

Special topics under investigation include multiphase systems and cryogenic fluids including the capillary channel flow (CCF) project, a two-phase system which has been utilized under microgravity conditions on the ISS and which required a significant number of preparatory investigations conducted in drop tower experiments [9, 10]. Cryogenic propellants will be used in the Ariane V upper stage; therefore, it is very important to explore the behavior of these fluids in microgravity to elucidate the underlying physical principles. These principles will be used to develop a computer simulation tool for the construction of thrusters.

Another active area of research is related to the investigation of boiling and heat transfer under microgravity conditions [11]. Novel configurations of bubble suspensions and heat transfer mediums (some incorporating nanoparticle suspensions) are created to study coalescence, phase change dynamics, and heat exchange in general in a turbulent medium under controlled conditions. This combines the physics of two-phase flows and thermal control which has importance for technology applications in both space and terrestrial applications.

6.7.4 Astrophysics

A main task of the experiments supporting astrophysics work is to determine parameters needed to estimate the characteristic time for the formation of planets, moons, and other solar system objects [12]. In particular, studies are conducted about the conditions under which elastic and inelastic scattering of dust particles, granular particles, small ice particles, or others occurs to form larger constituents (agglomeration). This phenomenon depends on the size and mass of the particles, their temperature, etc. Other external influences, such as light or thermal radiation, are also being investigated. Microgravity experiments revealed that the surface of Mars is efficient in cycling gas through layers, at least centimeters above and below the soil, with a turnover time of only seconds to minutes [13]. Clearly, such experiments must be conducted under microgravity conditions to properly simulate the conditions in space—planets and other objects that form under weightlessness condition. Besides this type of experiment's relevance to planetary sciences, this work may also have impact on material sciences, in particular, on the physics of granular materials.

6.7.5 Material Sciences

Particular problems in the area of material sciences such as the physics of granular gases, synthesis of nanomaterials, or the transport of fluids in porous materials are also being studied in microgravity environments. One aspect is to discover fundamental properties and synthesis pathways within these systems which are relevant for producing novel materials not able to be synthesized in normal gravity and supporting theoretical/statistical descriptions of these systems (and/or validating corresponding numerical simulations) [14, 15]. Another application of this work is for the transport of granular gases and of the transport of fluids through granular or porous media which has industrial applications including satellite technology. For satellite technologies, cryogenic fluids must be considered and properly characterized. This work is conducted in microgravity conditions in order to explore the fundamental physical principles without the disturbing gravitational force. The impact and relevance for industrial applications is obvious.

6.7.6 Biology

The experimental study of biological systems under microgravity or reduced gravity is in some cases of general interest but mainly for applications in space, on Moon, or on Mars to better understand how do organisms behave and how the nervous system reacts. In drop towers, only phenomena occurring on a short timescale can be investigated and this tends to limit biological applications. This includes the general behavior of microorganisms or the influence of microgravity on the orientation capabilities of complex organisms [16]. This work supports a better understanding of the general functioning of the nervous system but also is very important for estimating the reaction of life during long space travel or for its behavior under variable gravity conditions (Moon, Mars, etc.).

6.7.7 Technology Tests

Drop towers are also used for technology tests to operate and validate various systems prior to deployment in operational environments. Examples are tests of the behavior of heat pipes, the performance of accelerometers, or the functioning of release mechanisms. The full performance of high-precision accelerometers can only be explored under weightlessness conditions. At the drop tower Bremen, testing is conducted in support of the differential accelerometers for the French mission MICROSCOPE, aimed at testing the universality of free fall (also called weak equivalence principle), with an accuracy of 10^{-15}, which is two orders of magnitude better than what is possible on Earth. The accelerometers, built by ONERA in Paris, have a performance of 10^{-14} m/s^2/sqrt(Hz). For these accelerometers, the catapult of the Bremen drop tower with a free fall time of almost 10 s is used [17]. Also, the accelerometers to be used in the GRACE Follow-On geodesy mission will be tested in the Bremen drop tower.

Another technology validation program is the asteroid lander MINERVA (MIcro/Nano Experimental Robot Vehicle for Asteroid) of the Japanese Hayabusa 2 mission tested in the Bremen drop tower. The actual mechanism for taking soil samples that are planned to be brought to Earth has been tested and validated for functionality. In addition, the functioning of the release mechanism of mobile lander MASCOT (Mobile Asteroid Surface Scout) has been proven in the Bremen drop tower as cooperation projects between the German Aerospace Center DLR and the Japanese space agency JAXA. A last example of technology validation would include the tests of the heat pipes designed to cool the eROSITA camera system at a temperature of –95 °C. The validation testing demonstrated that the heat pipe system that was based on capillary forces is working very well and should perform well once deployed.

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