Topical: Earth-based platforms for microgravity research on ultra-cold atom devices for space applications

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On Earth, the second quantum revolution is about to expand our understanding of time-keeping, communication and sensing. Leveraging this revolution for space missions promises to probe up to now inaccessible regimes for a variety of different applications. In order to prepare the necessary technology for space, different microgravity platforms, like drop towers, aircraft or sounding rockets have been intensively used throughout the last almost two decades. Although, this research approach required substantial efforts, important milestones have been reached, like the demonstration of a Bose-Einstein condensate in space. With the advent of the novel microgravity platform Einstein-Elevator a dramatic boost in efficiency in enabling technology for the second quantum revolution for space missions is in reach. This white paper proposes a dedicated multi-user facility for the Einstein-Elevator for research on ultracold atom technology for space applications. With this facility, a broad range of experimental capabilities will be covered and its accessibility and modularity will additionally allow for flexible exchange or addition of capabilities for future developments.

1 INTRODUCTION

Microgravity offers a unique environment for experiments with cold atoms [1]. It enables the observation of atomic ensembles after extended free-fall times, the gravitational sag vanishes, and ensembles can be placed at specific locations without requiring additional methods to compensate for gravity. Consequently, proposals for testing the universality of free fall [2–4], for earth observation [5–7], for gravitational wave detection [8–12], and for other topics [13] utilizing atom interferometry anticipate a significant performance boost in space missions. More research opportunities on cold atoms emerge [1], including quantum reflections [14], space atom lasers [15], bubble shells [16–19], and mixtures [20–22].

To develop the necessary hardware and atom-optical techniques for such space missions, Earth-based microgravity platforms have proven their great benefit. Although they cannot fully simulate the demands of a full space mission, especially the ultra-long duration of microgravity, these platforms allow for very good access to the experimental setup and can accumulate minutes to hours of microgravity.

Over the last two decades, research on cold and ultra-cold matter on microgravity platforms was pioneered by the I.C.E consortium facilitating the Zero-G parabola flight weightlessness lab [23] and, in particular, by the QUANTUS collaboration operating at the Drop Tower Bremen [24]. I.C.E was flown on multiple parabola campaigns each giving access to 22 s of weightlessness. This experiment demonstrated the first airborne matter-wave inertial sensor [25] and operated two simultaneous interferometers of rubidium and potassium, which enabled the first test of the weak equivalence principle in a free-falling vehicle [26]. At the Drop Tower Bremen, QUANTUS-1 and QUANTUS-2 were operated 800 times in total since 2007 with 4.7 s of microgravity in the drop mode and 9.3 s in the catapult mode, accumulating in this way over one hour of microgravity within 14 years. During these experiments, the first Bose-Einstein condensate in microgravity was demonstrated by QUANTUS-1 [27]. Subsequently, the first matter-wave interferometry experiment on a Bose-Einstein condensate in microgravity was reported [28]. With the advent of the second generation experiment QUANTUS-2, a high-flux source of Bose-Einstein condensates [29] began its operation at the Drop Tower. This more efficient and more compact apparatus is compatible with the catapult mode of the Drop Tower, extending the capabilities to four Bose-Einstein condensate experiments within a single catapult flight [30]. Recently, this apparatus demonstrated the best three-dimensional collimation of a matter-wave down to 38 pK by means of a collective-mode excitation in combination with a magnetic matter-wave lens [31].

In addition to atom-chip based setups for ultra-cold atoms in microgravity, optical dipole traps are investigated in the PRIMUS project at the Drop Tower Bremen. Within this project a compact experimental setup was realized [32]. The implementation of a single beam optical dipole trap in microgravity, successful evaporative cooling in weightlessness and the advancement to a crossed beam configuration were demonstrated [33].

Based on these successful experiments in the Drop Tower Bremen, the MAIUS collaboration brought for the first time ultra-cold matter into space, creating and performing multiple experiments on Bose-Einstein condensates on-board a sounding rocket [34]. During the six-minute space flight the coherence of the ultra-cold atomic ensembles was demonstrated by atom interferometry [35]. This platform required further technological development due to limitations in mass, volume and power consumption of the apparatus as well as increased robustness because of high vibrational loads and shocks during launch and re-entry into the atmosphere. Additionally, autonomous operation capability is mandatory because a data link can not be guaranteed. The mission MAIUS-1 significantly increased the technological readiness level (TRL) of atom interferometers for space applications and served as a pathfinder for in-orbit missions. Two follow-up missions MAIUS-2 and -3 are currently in preparation and will investigate dual-species experiments in the absence of gravity [22].

Parallel to these efforts, NASA has set up its Cold Atom Lab (CAL) on the International Space Station (ISS) and demonstrated the first BEC in orbit [36] and recently observed ultra-cold atomic bubbles in orbital microgravity [37].

These developments led to the formation of the NASA-DLR collaboration for the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL), a multi-user facility for research on ultra-cold atoms on the ISS [1].

Nowadays, actively driven platforms for microgravity research are about to take over. As a demonstrator, the I.C.E experiment has been installed in an active 0 g simulator, which provides up to half a second of weightlessness on every trajectory with a repetition rate of one parabola every 12 s. This device has been specifically constructed to operate the I.C.E. experiment only. At the Bremen Drop Tower, the GraviTower Bremen Prototyp renders a next generation of drop towers at the Center of Applied Space Technology and Microgravity [24]. This platform is designed to fit the same proven experiment designs and dimensions as used in the Bremen Drop Tower making both facilities fully compatible. With an anticipated repetition time of five minutes, each flight will offer 2.5 s of microgravity.

At the forefront of the actively driven platforms for microgravity research, the Einstein-Elevator at Leibniz University Hannover/HITec, recently started its operation [38]. Here, 300 actively controlled vertical parabola flights per day of up to 4 s duration can be provided. By this, accumulating one hour of microgravity time will not anymore take 14 years, but only few days of operation. The Einstein-Elevator has the capability of simulating the full range of gravity conditions from hypergravity (e.g. rocket launch), to hypogravity (e.g. Moon or Mars) down to microgravity. It offers long free-fall times and the possibility to acquire extensive statistics over days or even weeks of integration. Consequently, the Einstein-Elevator provides the opportunity to operate a multi-user facility for research on ultra-cold atoms in microgravity and to validate concepts for space missions.

2 The Einstein-Elevator

The Einstein-Elevator is an active drop tower [39]. A gondola, the central component of the facility, is driven by linear motors that compensate for air drag and guidance friction or even vary the acceleration between microgravity and increased gravity of up to 5 g.

The gondola encloses the pressure-tight carrier of the experimental setup so that the gondola can be evacuated to a pressure of 10^{-2} mbar. After the initial acceleration the carrier can be decoupled from the gondola which then follows at a drive-controlled distance of about 50 mm during the parabolic flight. This way the free fall of the carrier is independent from the disturbances of the environment for example for acoustic decoupling.

With a total height of 40 m the Einstein-Elevator offers up to 4 s of microgravity time during the 20 m vertical parabolic flight and with a residual acceleration below $10^{-6}\,g$. After every flight the electromagnetic drive system requires a break of roughly four minutes to cool-down, recharge the energy storage system, recenter the carrier inside the gondola without opening it, restore the vacuum quality and set new test parameters. In total, a maximum number of 300 flights can be executed per day [41–43].

In comparison to other microgravity platforms the constraints on the experimental setup are relatively low. It offers a payload space of 1.7 m in diameter and a height of 2.0 m, a maximum mass of 1,000 kg, telemetry data, an uninterruptible power supply and a continuous data connection between the experimental setup and the operator station in the control room. The maximum acceleration during start and landing of the parabolic flight is 5 g. During the break between flights the Einstein-Elevator provides water cooling, additional power supply for charging internal batteries and the constantly available network connection. The different flight phases can be communicated to the experimental setup via trigger signals.

The facility just recently started operation and the first experiments with ultracold atom devices are in preparation. The high repetition rate of the flights enables a higher number of data points within a reasonable time and financial frame in comparison to other platforms. This can be relevant for statistical measurements that do not necessarily require continuous microgravity. For example, it can be used to calibrate setups for later space missions. The variation of acceleration can help to develop models that describe the transfer of certain processes from 1 g to 0 g. These simulations could calculate optimizations

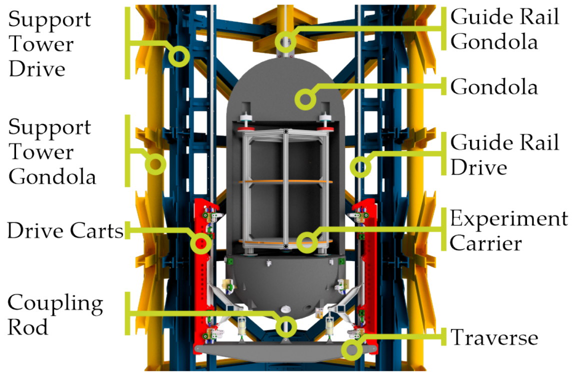

Figure 1
Setup of the Einstein-Elevator (based on C. Lotz, et al., Adv. Space Res. 61, 1967–1974 (2018) [39], licence: CC-BY 4.0 [40])

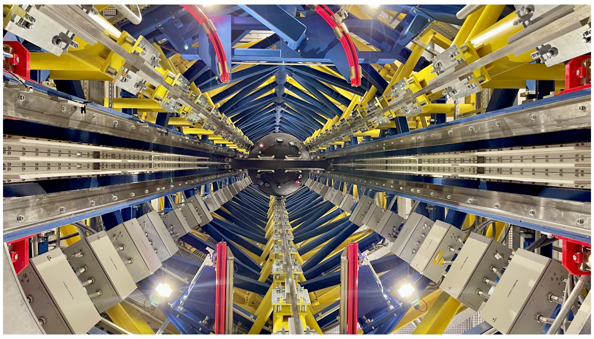

Figure 2
Gondola of the Einstein-Elevator during a vertical parabolic flight (credit: Leibniz University Hannover/Christoph Lotz, licence: CC-BY 3.0 DE [44])

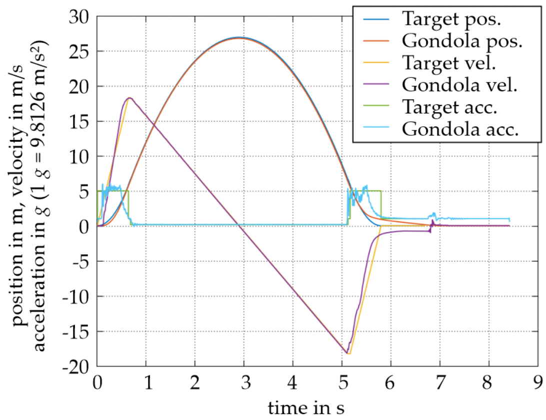

Figure 3
Parabolic flight profile of the Einstein-Elevator (based on C. Lotz, et al., Logistics Journal: Proceedings 2020 (2020) [42], license: f-DPPL v1 de 11-2004 [45])

for the operation in space. Applications reach from the transport of an atomic ensemble via magnetic fields to delta-kick collimation.

Due to the low constraints on the experimental setup and the high repetition rate of the flight executions the Einstein-Elevator is an ideal platform for proof-of-principle measurements. The used technology needs to fulfill a lower technological readiness level than for space missions. The easy access to the apparatus allows for further improvements and exchange of hardware. This combined with comparably low financial costs also enables a possible funding of experiments with increased risk of failure.

3 A MULTI-USER FACILITY FOR ULTRA-COLD SCIENCE IN THE EINSTEIN-ELEVATOR

As outlined in the previous sections, the Einstein-Elevator provides a unique platform for experiments on ultra-cold atoms in microgravity without the tight restrictions applicable for other, especially space-borne, systems. We envision a multi-user facility similar to CAL [36] or BECCAL [1] adapted to the Einstein-Elevator and housing a broad range of experimental capabilities, like different atomic species, trap configurations, and methods for manipulation of internal and external degrees of freedom. This device offers a direct comparison between experiments in microgravity and gravity within the same apparatus, direct user access between experimental runs e.g. for alignment or fine-tuning, and the possibility for a modular design to exchange or add capabilities. Modularity and direct access reduce the overhead on developments for installing new functionalities. One hundred flights within a working day ensure reasonable statistics, parameter sweeps, or 'hands-on' optimization, whereas higher cycle rates on ground enable detailed tests of sequences beforehand. The design may support detailed studies on delta-kick collimation [31], mixtures [20–22], bubble geometries [16–19], and atom interferometry for future space-borne quantum sensors. Supported by the modular design, more specific design requirements for experiments on dark energy detection [13, 46, 47], squeezing [48, 49], determining the gravitational constant [50, 51], or special optical / blue detuned traps [52–56] may be implemented.

4 CONCLUSION

Earth-based microgravity platforms have proven their benefit for advancing quantum technologies for space applications. By using platforms, like drop towers, aircraft or sounding rockets, important milestones for experiments on ultra-cold atoms have been reached. As demonstrated by this success, research using microgravity platforms is vital and will continually add important insights for the preparation of space missions. Thanks to the recent commissioning of the Einstein-Elevator, an outstanding novel platform for research on quantum technologies is at hand. Facilitating this microgravity platform by establishing a multi-user facility for ultra-cold atom research will dramatically speed-up the development of quantum technologies for space applications. Setting up such a multi-user facility would be a prominent evolution for Earth-based microgravity research on ultra-cold atom devices for space applications.

5 LICENSE

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