Draft, February 2004, modified after discussions with E. Polacco, D. Bramanti and G.L. Comandi

"Galileo Airborne Test of Equivalence"-GATE

A.M. Nobili†, C S Unnikrishnan‡ and Suresh D*
† University of Pisa and INFN, Pisa, Italy
‡ Tata Institute of Fundamental Research, Bombay, India
**Indian Institute of Astrophysics, Bangalore, India*

Abstract

A differential Galileo-type mass dropping experiment named GAL was proposed at the University of Pisa in 1986 [1] and completed at CERN in 1992 [2] in order to test the equivalence principle by testing the universality of free fall. The free falling mass was a disk made of two half disks of different composition; a violation of equivalence would produce an angular acceleration of the disk around its symmetry axis, which was measured with a modified Michelson interferometer. GATE -"Galileo Airborne Test of Equivalence" is a variant of that experiment to be performed in parabolic flight on-board the "Airbus A300 Zero-g" aircraft of the European Space Agency. The main advantages of GATE with respect to GAL are the longer time of free fall and the absence of weight in the final stage of unlocking. The longer time of fall makes the signal almost 500 times stronger and allows a spurious linear growth of the rotation angle to be separated out. Moreover, unlocking at zero-g can significantly reduce spurious angular accelerations of the disk due to inevitable imperfections in the locking/unlocking mechanism which turned out to be the limiting factor in GAL [2]. A preliminary estimate indicates that GATE should be able to achieve a sensitivity $\eta \equiv \Delta g / g \simeq 10^{-13}$, an improvement by about 3 orders of magnitude with respect to GAL and by about 1 order of magnitude with respect to the best result obtained with a slowly rotating torsion balance. Ground tests of the read-out and of the locking/unlocking disturbances can be carried out prior to the aircraft experiment.

1 Experimental apparatus in parabolic flight

The GATE experimental apparatus is carried on-board the "Airbus A300 Zero-g" aircraft of ESA during a campaign of parabolic flights. It consists of a cubic vacuum chamber of 1m side inside which a disk made of two half disks of different composition is attached with its center at the center O of the chamber and the plane of the disk parallel to one face of the chamber (see Fig. 1). Let σ be the symmetry axis of the disk and ρ the axis, perpendicular to it, lying in the plane of the disk, passing through its center and separating the two half disks from one another. If the local vertical were directed along ρ and the disk were in free fall, a deviation from the universality of free fall, hence a violation of the equivalence principle, would produce an angular acceleration of the disk around its symmetry axis σ. The disk is rigidly attached to the chamber through an appropriate locking-unlocking device which can also be rotated from remote around the axis ρ (together with the disk) by 180°, so as to reverse the sense of rotation in case of violation.

Since in free fall there is no way to identify the local vertical, this is done from the knowledge of a typical aircraft parabolic maneuver, particularly from the a-priori knowledge of the aircraft attitude with respect to the surface of the Earth at the time when free fall begins, e.g. from the a-priori knowledge of the direction of the local vertical with respect to the aircraft floor at that time. We assume this direction to be known within a few degrees, and call this axis τ. We lock the vacuum chamber to the aircraft cabin with its axis ρ parallel to τ, so that after unlocking they remain parallel to each other during free fall within the errors caused by unlocking. Since unlocking errors are likely to be smaller than the uncertainty due to aircraft maneuvers, we assume that during free fall the local vertical will lie in the plane of the disk within a few degrees. Therefore, only a small fraction of the local acceleration of gravity will not contribute to the driving signal of a possible deviation from the universality of free fall.

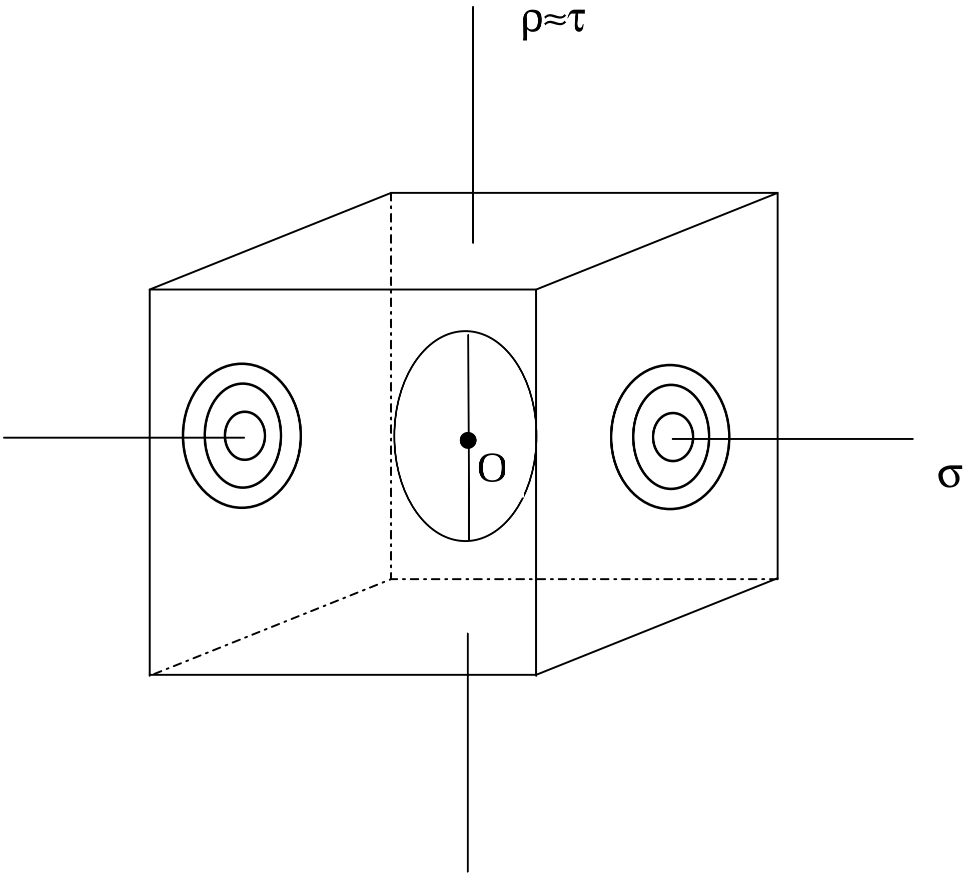

Figure 1. Schematic view of the GATE vacuum chamber showing the disk at its center, the 3 locking/unlocking rings of the chamber, the disk symmetry axis σ and the axis ρ, close to the direction τ of the local vertical at free fall. The locking/unlocking rings of the disk, its attachment to the chamber and the read-out system are not shown; the telescopic arm and its connection to the locking/unlocking rings of the chamber are not shown either. (Figure is not too scale: the disk as well as the locking/unlocking rings are much smaller relative to the chamber)

Two corner cube reflectors are mounted on the rim of the disk like in GAL (see [2], Fig. 2) while all other components of the laser interferometer for measuring the angular rotation of the disk around its symmetry axis σ are mounted on the vacuum chamber. A deviation from the universality of free fall would show up as an angular acceleration around this axis. Spurious rotations of the disk (relative to the vacuum chamber) around two orthogonal axes in the plane perpendicular to σ can be measured with a position sensitive detector (e.g. like PSD S2044 by Hamamatsu) together with a laser, attached to the chamber, and a small mirror mounted on the plane of the disk. The absolute rotation of the vacuum chamber in all 3 degrees of freedom (relative to inertial space) can be measured with 3 gyroscopes based on the Sagnac effect.

A radio transmission system between the chamber and the aircraft cabin (for sending commands and acquiring measurement data in real time) is also attached to the chamber. The chamber is evacuated on the ground before boarding the Airbus A300 Zero-g aircraft, and has getter pumps inside to maintain vacuum for the duration of the flight. A residual pressure of the order of $10^{-6}\,\mathrm{mbar}$ can be achieved and is fully adequate for the experiment. Typically 30 parabolas, lasting about 1 minute each, are performed during each day of flight, and an entire A300 Zero-g campaign lasts 3 days. Care is taken in avoiding any moving parts and also in maintaining the spherical symmetry of the chamber.

According to the User's Manual of Airbus A300 Zero-g aircraft [3] during the 20 to 25 seconds of the parabolic maneuver, the residual gravity level for any apparatus attached to the aircraft structure is about $10^{-2}g$. The resulting relative motion between the free falling disk and the vacuum chamber would be far too large were it attached to the aircraft during measurements; the vacuum chamber must therefore be unlocked from the aircraft during free fall. However, since the aircraft is subject to disturbing accelerations as large as $10^{-2}g$, the vacuum chamber would require as much as $30\,\mathrm{m}$ in order not to hit the cabin during free fall. However, the aircraft is capable of following the so called "free-float procedure" whereby piloting is done with respect to keeping an object free-floating in the middle of the cabin (visible for the pilots on a video screen) [3]. The "free-float procedure" is therefore required for each parabolic flight of the GATE experiment. Assuming that an entire A300 Zero-g 3-day campaign can be devoted to the experiment, it would allow us to perform up to 90 measurement runs.

An experiment similar to GATE was proposed to NASA in 198? [4] and approved for a space shuttle flight. Unfortunately, it was canceled following the Challenger disaster in January 1986.

2 Locking, unlocking and recovery of the vacuum chamber

The vacuum chamber, fully equipped to perform a test of the universality of free fall, must be covered with foam padding for safety reasons. At all times except during measurement in free fall the disk is locked and the chamber is attached to the aircraft cabin through a motorized telescopic arm. The arm can bring the chamber from near the cabin wall to about its center and back. The arm terminates with a clamping system made of two "hands", to be locked/unlocked with a single switch. The telescopic arm will place the vacuum chamber close to the center of the cabin with its ρ axis as parallel as possible to the vertical direction τ and unlocking is performed as soon as free fall begins

The two "hands" of the telescopic arm clamp the chamber at the opposite ends of the axis σ. We envisage a 3-stage locking/unlocking device of the chamber. For each stage the two "hands" are a pair of flat rings α,β,γ of decreasing radius, so that each ring is located inside the other in a nested configuration. Each pair of rings contains mechanical springs (symmetric around the ring axis) so that the two rings of each stage can provide a clamping force along the direction σ. The springs of the largest ring pair α must be capable of withstanding the acceleration of the Airbus A300 Zero-g aircraft during the initial ascending phase of each parabola, namely $1.8g$; the springs of ring pair β provide $10^{-2}g$ and those of ring pair γ provide $10^{-5}g$. Each pair of rings is unlocked by a single switch; the ring pairs α,β,γ are unlocked in rapid succession immediately after the aircraft has switched off the engines and free fall begins. Since disturbances due to inevitable asymmetries and imperfections in the unlocking system are proportional to the strength of the locking, a 3-stage unlocking system of decreasing strength will minimize such disturbances. A 2-stage system may not be effective because if the second stage is weaker than the first one by many orders of magnitude, it may be affected by the unlocking of the first stage even if locked. The metallic surface of the chamber is covered with appropriate rubber in order to absorb and damp vibrations of the whole chamber which may nevertheless result from unlocking, since foam padding (which will cover the rubber) may not be sufficiently dense for such damping. During the entire unlocking phase of the chamber the disk inside it is locked, so that no relative motion between the two is produced. For the complete 3-ring locking system to be positioned symmetrically around the axis σ the largest rings α have a carved allocation on the surface of the chamber so that once they are in place, the ring pairs β and γ are also symmetric around the σ axis. The vacuum chamber has a loose wire to allowing its recovery at the end of each parabolic flight, immediately before the aircraft accelerates to begin the ascending phase of next parabola; once recovered, the chamber is locked by putting the two rings α in place, which automatically ensures that rings β,γ are also locked.

3 Locking/unlocking of disk

The disk is locked to the chamber by 3 pairs of rings $\alpha_d, \beta_d, \gamma_d$ of decreasing radius, each pair centered at the center of the disk and the two rings facing the disk from opposite sides. As for the locking rings of the chamber, these 3 pairs of rings have springs providing $1.8g$, $10^{-2}g$ and $10^{-5}g$ respectively along the symmetry axis of the disk. Immediately after the last pair of rings γ of the chamber has been unlocked, the first pair of rings α_d of the disk is unlocked, then β_d and finally γ_d. The disk edge is shaped like in a pulley in order to allocate a rubber O-ring to absorb and damp residual vibrations of the disk which might nevertheless result from unlocking disturbances. In this case too the 3-stage unlocking is meant to minimize any residual disturbing motion of the disk relative to the chamber, in particular an angular acceleration around the disk axis which would mimic a violation of equivalence and therefore limit the sensitivity of the experiment. A residual constant angular velocity of the disk around its axis would result in a linear growth of the rotation angle with time, and can therefore be separated out from the quadratic growth of the signal. However, since the corner cube laser retro reflectors are attached to the disk, while beam splitters, mirror and lenses of the laser interferometer are attached to the chamber, the total rotation angle (as a matter of fact the total relative motion of the disk with respect to the chamber) should be small enough not to impair the performance of the read-out.

Because of the free fall and the residual extremely small relative motion between the disk and the chamber, locking back the disk to the chamber at the end of free fall is not a difficult task. A self adjusting mechanical system will be designed such that the ring pair α_d can be clamped back in place, centered on the symmetry axis of the disk. In doing this the ring pairs β_d and γ_d will also be automatically back in place. Immediately after disk locking, the vacuum chamber recovery and clamping is performed, to be completed immediately before the end of free fall and the beginning of the ascending accelerated phase of the next parabola. The purpose is to use for locking, unlocking and recovery operations of chamber and disk the smallest possible fraction of the total free fall time of the aircraft, while also making sure that all these operations are performed while in free fall, and not during the acceleration phase of each parabolic flight.

4 Preliminary estimate of expected sensitivity

Except for the locking/unlocking procedure described above we envisage a baseline experiment just as in [2]. The disk is made of two half disks of *Al* and *Cu* respectively weighing about 347 g each, having the same moments of inertia in the plane perpendicular to the symmetry axis of the disk (to about 1 part in 10^3) and the centers of mass both at distance $b = 2.4\,\mathrm{cm}$ from the axis. A modified Michelson interferometer in all similar to the one used in [2] can read both the angular velocity and the angular acceleration $\dot{\omega}$ of the disk around its axis, the latter being non zero should the equivalence of inertial to gravitational mass between *Al* and *Cu* be violated to the level $\Delta g/g = \eta$ ($\dot{\omega} \simeq \eta g/b$). The total rotation angle of the disk with a free falling time t_{ff} is $\alpha_{EP} \simeq \eta g t_{ff}^2 / 2b$. Since it grows quadratically with the time of free fall, the advantage of GATE with respect to GAL is apparent. In GAL the free fall height was about $4\,\mathrm{m}$ (the vacuum chamber was $8\,\mathrm{m}$ high but about half of it was need for breaking the disk inside it) [2], hence the free fall time was $0.9\,\mathrm{s}$. Assuming that in GATE no more than $5\mathrm{s}$ are needed in total for unlocking and locking of both chamber and disk, a free falling time of $20\,\mathrm{s}$ is available, resulting in a signal almost 500 times larger.

The sensitivity achieved by the GAL experiment was of a few parts in 10^{10}; measurements carried out with a disk whose two half disks were made of the same material showed that the limitation was not due to the sensitivity of the read out interferometer but rather to a spurious angular acceleration of the disk due to imperfections in its unlocking mechanism. While it is true that in GATE not only the disk but also the vacuum chamber requires to be unlocked, it is possible to exploit the very peculiar fact that both chamber and disk can be unlocked at zero-g, at least at the final stage. And since spurious disturbances due to asymmetries and imperfections of the unlocking are necessarily a fraction of the locking strength required, we are confident that at least a factor 50 of reduction in such disturbances as compared to the GAL experiment can be achieved. As for the read out, the disk total rotation angle resulting from a violation of equivalence $\eta \simeq 10^{-13}$ in a free fall time of $20\,\mathrm{s}$ is as large as about $8\times10^{-9}\,\mathrm{rad}$, which can surely be detected. Up to 90 measurement runs can be performed in a 3-day campaign of Airbus A300 Zero-g aircraft. The disk (together with its locking/unlocking mechanism) can be rotated by 180° around the vertical axis passing through its center from one measurement run to the next in order to check the sign of the rotation angle. The total mass of the disk could be increased should thermal noise vibrations limit the sensitivity of the experiment. Different pairs of materials can be tested.

Residual air inside the cabin acting on the outer surface of the vacuum chamber and not on the disk (the disk is unlocked during measurements) will cause a relative motion between the two that will affect the read-out laser interferometer system, because part of it is attached to the disk (e.g. the retro-reflectors) and part to the chamber. If we assume that the relative velocity of the air with respect to the chamber is about $0.1\mathrm{m}$, the drag acceleration is $\simeq (A/M)\rho_{air}v^2 \simeq (1/100)\cdot 1\cdot (0.1)^2 \simeq 10^{-4}\,\mathrm{ms}^{-2}$, which in $20\mathrm{s}$ would produce a relative displacement of $2\mathrm{cm}$ at most (assuming it would act in the same direction for the entire duration of the free fall). The retro-reflectors must be no smaller than this size for the laser interferometer to operate in the presence of such disturbance. In addition, a non uniform pressure on the outer surface of the vacuum chamber would produce an angular rotation relative to the disk. The amount of this rotation should be evaluated quantitatively and compared to the angular acceleration in case of a violation of equivalence to the level $\eta \simeq 10^{-13}$. Although any rotation of the chamber is measured, one should consider the possibility of eliminating altogether any disturbance from residual air in the cabin by enclosing the vacuum chamber inside a larger one, just for shielding purposes. In doing this, the read-out being located partly on the disk and partly on the inner chamber, would be totally unaffected by air. An additional locking/unlocking ring system should be added, similar to the ones used for the inner chamber and the disk.

Prior to performing the experiment on-board the Airbus A300 Zero-g aircraft the entire GATE apparatus is suspended in the laboratory against local gravity and disturbances resulting from the unlocking mechanism in the horizontal plane are directly measured. Inside the chamber, the disk is also suspended and the disturbances of its own unlocking mechanism are measured in the horizontal plane, checking their effects on the performance of the read-out. The radio link is tested, as well as the total time required for the locking/unlocking procedure. The design, construction and testing of the experimental apparatus can benefit largely from the expertise acquired with the GAL experiment.

5 Conclusions

A preliminary analysis indicates that the experiment GATE-“Galileo Airborne Test of Equivalence” on-board the Airbus A300 Zero-g aircraft of ESA could test the Universality of Free Fall to about 1 part in 10^{13}. This would be an improvement by about 3 orders of magnitude with respect to a similar Galileo differential experiment at $1\text{-}\mathrm{g}$, and by about 1 order of magnitude with respect to slowly rotating torsion balance tests [5]. GATE could either confirm or rule out recent predictions of a possible violation of equivalence slightly below 10^{-12} [6,7].

References

[1] V. Cavasinni, E. Iacopini, E. Polacco, G. Stefanini, Phys. Lett. A 116, 157 (1986)
[2] S. Carusotto, V. Cavasinni, A. Mordaci, F. Perrone, E. Polacco, E. Iacopini, G. Stefanini, Phys. Rev. Lett. **69** 1722-1725 (1992)
[3] Parabolic Flight Campaign with A300 ZERO-G, User's Manual http://www.novespace.fr/VEnglish/Microgravity_a/man_vola/flightUserManual.htm
[4] R. Cowsik (198?)
[5] S. Baeßler, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, U. Schmidt, H.E. Swanson, Phys. Rev. Lett. **83** 3585 (1999)
[6] T. Damour, F. Piazza, G. Veneziano, Phys. Rev. D **66**, 046007 (2002)
[7] T. Damour, F. Piazza, G. Veneziano, Phys. Rev. Lett. **89**, 081601-1 (2002)