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The dynamics of parabolic flight: flight characteristics and passenger percepts

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Abstract

Flying a parabolic trajectory in an aircraft is one of the few ways to create freefall on Earth, which is important for astronaut training and scientific research. Here we review the physics underlying parabolic flight, explain the resulting flight dynamics, and describe several counterintuitive findings, which we corroborate using experimental data. Typically, the aircraft flies parabolic arcs that produce approximately 25 seconds of freefall (0 g) followed by 40 seconds of enhanced force (1.8 g), repeated 30–60 times. Although passengers perceive gravity to be zero, in actuality acceleration, and not gravity, has changed, and thus we caution against the terms "microgravity" and "zero gravity." Despite the aircraft trajectory including large (45°) pitch-up and pitch-down attitudes, the occupants experience a net force perpendicular to the floor of the aircraft. This is because the aircraft generates appropriate lift and thrust to produce the desired vertical and longitudinal accelerations, respectively, although we measured moderate (0.2 g) aft-ward accelerations during certain parts of these trajectories. Aircraft pitch rotation (average 3°/s) is barely detectable by the vestibular system, but could influence some physics experiments. Investigators should consider such details in the planning, analysis, and interpretation of parabolic-flight experiments.

Keywords

Parabolic flight; freefall; otolith; gravity; zero g; weightlessness

1. Introduction

High-performance aviation and space flight have dramatically changed the forces and accelerations to which humans are exposed. During space flight humans have experienced freefall, which requires the body to operate in an environment different from the constant gravitational environment in which it evolved. Research to understand the effects of freefall on the body is important for sustaining humans during long-duration spaceflight, especially during taxing operational tasks. In addition, some research in physics and chemistry can only

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be performed in freefall, such as the study of fluid mechanics as applied to fuel flow in spacecraft.

It is important to distinguish between “freefall” and “weightlessness.” Even in orbital flight, for example when the Space Shuttle orbits 300 km above the Earth's surface, gravity is only slightly less than at sea level (9.37 m/s^2 compared to 9.81 m/s^2 at sea level). Thus terms like “microgravity,” “zero-gravity,” and “weightless” are technically incorrect when applied to orbital flight (and atmospheric aircraft maneuvers), although they are often used to describe the *perception* that astronauts experience during freefall. Spacecraft in Earth orbit are continually falling toward the earth under the force of gravity, but are given sufficient forward velocity so that the sum of their velocities toward and parallel to earth keeps them at the same distance from earth; as the spacecraft falls toward the earth, the earth curves away from under it. Astronauts *perceive* themselves to be weightless because they are falling under the influence of the same gravitational field as the spacecraft, so there is no reaction force on the astronaut by the spacecraft. According to Einstein's equivalence principle, no simple physical transducer can determine whether an applied acceleration is due to gravitational or inertial force, and this includes the sensors in the human body. Gravito-inertial acceleration (GIA), often expressed simply as *g* level, is defined as the sum of the linear accelerations due to gravity and inertial forces. It is measured in units of *g*, where $1 \text{ g} = 9.81 \text{ m/s}^2$ at sea level. During freefall the net *g* level is 0 *g*, but gravity is not zero.

Although space flight is the only way to provide long periods of true freefall, a much cheaper and more accessible method is available in an aircraft flying a parabolic trajectory. During such parabolic flight an aircraft flies a trajectory that provides freefall for up to 40 seconds. Parabolic flight generates freefall by following a trajectory wherein the acceleration of the aircraft cancels the acceleration due to gravity (Figure 1), along the aircraft vertical (*z*) axis. Essentially, if the aircraft and its occupants “fall” together at 9.81 m/s^2 , “0 *g*” is achieved, where there is no reaction force on the occupants by the aircraft. Such a flight typically consists of 30 to 60 parabolas, each providing about 25 seconds of freefall. Between parabolas, the aircraft must climb to regain altitude, and during this 40 second interval when downward velocity is reduced and eventually becomes upward velocity, *g* levels reach 1.8 *g*. (Contrary to popular misconception, the 0 *g* freefall phase of flight begins as the aircraft climbs, and does not occur solely as the aircraft descends. Although the aircraft has upward *velocity* during the initial 0 *g* phase, its *acceleration* is downward: the upward velocity is decreasing.)

Parabolic flight as a platform for astronaut training and engineering experiments was originally proposed in 1950 by Drs. Fritz Haber and Heinz Haber, of the Air Force School of Aviation Medicine, Brooks Air Force Base, Texas [1]. Early experimentation with the technique was conducted by legendary test pilots Scott Crossfield and Chuck Yeager in 1951 at Edwards Air Force Base, California, although initially only a few seconds of true freefall could be achieved, compared with 30 seconds envisioned by the Habers [2]. Between 1955 and 1958, a refined approach in the F-94 fighter allowed a variety of medical experiments to be performed during 30 to 40 seconds of freefall [3]. Between 1957 and 1959, the much larger C-131B cargo transport allowed simultaneous experiments on multiple subjects [4] and sufficient room for Mercury program astronauts to train (Figure 2), although this slower, propeller-driven aircraft could only produce parabolas with 10 to 15 seconds of freefall.

2. Reaction forces of the aircraft on the occupants

A challenge in performing parabolic flight maneuvers is to fly in a way that keeps occupants in the same location and orientation relative to the aircraft, despite the aircraft being tilted a maximum of more than 45° relative to the earth and rotating in pitch through approximately 90° in 30 seconds (Figure 1). Ideally, forces between the occupants and the aircraft are only

along the vertical axis of the aircraft, so that even if the aircraft is pitched up or down significantly, the occupants will not have longitudinal translation forces along the length of the aircraft, nor forces toward the sides of the aircraft. Additionally, any rotation of the aircraft should be minimal so that the occupants do not sense rotation relative to the aircraft; this is true for undesired roll and yaw rotations, as well as pitch rotations which are unavoidable in flying a parabolic arc. The aircraft is flown along a precise trajectory so that, ideally, the forces on the occupants change along only one degree of freedom (vertical). Here we derive the motion required of the aircraft to meet this condition.

2.1 Forces due to linear motion

We choose for our analysis a coordinate system fixed to the aircraft, where the x-axis is the longitudinal axis going from the front to the back of the aircraft, and the z-axis is the vertical axis. θ is the pitch angle of the aircraft with respect to the earth horizontal (Figure 3). We define m as the mass of a person aboard the aircraft, and $W=m \cdot g$ as the weight of the person due to the constant 1 g of Earth's gravitational field. W_x and W_z are the projections of W along the x and z axes of the aircraft's co-ordinate system, respectively. The reaction forces between the person's feet and the aircraft are labeled N_x and N_z . The net accelerations of the person projected along the aircraft's longitudinal and vertical axes are labeled a_x and a_z .

Parabolic flight is designed to make N_z and a_z near zero during freefall (0 g), while minimizing N_x and a_x subject to aerodynamic constraints. Forces along the lateral (y) axis are minimal because the aircraft is flying straight, usually under precise autopilot control.

Along the vertical axis of the aircraft,

$$\sum F_z = m \cdot a_z = -W_z + N_z.$$

During the 1.8 g phase of flight, the normal force between the floor and the occupant is 1.8 $N_z = 1.8 W$, so:

$$\begin{aligned} \sum F_z &= m \cdot a_z = -W \cdot \cos\theta + 1.8W \\ a_z &= (1.8 - \cos\theta)g. \end{aligned}$$

During the 0 g phase of flight, the normal force between the floor and the occupant is $N_z = 0W$, so:

$$\begin{aligned} \sum F_z &= m \cdot a_z = -W \cdot \cos\theta + 0W \\ a_z &= (0 - \cos\theta)g = -g\cos\theta. \end{aligned}$$

During 0 g the acceleration along the aircraft vertical is always negative, and becomes less negative as the pitch angle becomes larger.

Along the longitudinal axis of the aircraft,

$$\sum F_x = m \cdot a_x = W_x + N_x = W \cdot \sin\theta + N_x.$$

But the occupant should not move along the floor of the aircraft (no "longitudinal g's": $N_x = 0$), so,

$$\sum F_x = m \cdot a_x = W \cdot \sin\theta + 0$$

$$a_x = g \cdot \sin\theta.$$

This shows the relationship between pitch angle θ , and forward acceleration a_x set by control of engine thrust, that must exist in order to minimize undesired fore-aft forces on the occupants.

2.2 Rotational dynamics

Since the aircraft is a rigid body, linear accelerations are equal across its structure. However, rotation of the aircraft creates additional forces that vary along the length of the aircraft. At the center of gravity of the aircraft these rotations cause only torques. However, away from the center of gravity they create both centripetal accelerations toward the center of the aircraft and tangential accelerations along the vertical axis. In addition to linear translation, the pitch attitude of the aircraft changes dramatically during parabolic flight. During one parabola, the aircraft changes pitch from approximately 45° nose-up to 45° nose-down, in approximately 30 seconds. This results in an average angular velocity ω of:

$$\omega = \frac{\Delta\theta}{\Delta t} = \frac{45^\circ - (-45^\circ/\text{sec})}{30\text{sec}} = 3^\circ/\text{sec}.$$

This near-constant angular velocity acts about the aircraft center of gravity, which produces a centripetal acceleration at the ends of the aircraft. We assume a maximum lever arm of 20 m (based on the length of 41 m of the KC-135 aircraft), producing a centripetal acceleration of:

$$a_c = \omega^2 r = \left(3^\circ/\text{sec} \times \frac{\pi}{180} \text{rad/deg}\right)^2 \cdot 20\text{m} = 0.055\text{m/s}^2 = 6/1000g.$$

This force acts along the longitudinal axis of the aircraft, and thus could create a reaction force on occupants in the fore-aft direction. This acceleration is below the amplitude of vibration in the aircraft, although it does act in a consistent direction. For example, a 50 kg individual would experience a force of 3 N (0.7 lb). During 1.8 g this would be perceived as a frictional force at the feet.

During the transition from the 1.8 g to the 0 g phase of flight, when the aircraft pitch is 45° nose-up, there is a change in angular velocity from rotating toward nose-up to rotating toward nose-down. Based on actual accelerometer recordings, this transition takes more than 3 seconds, which yields an approximate average angular acceleration α of:

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{3^\circ/\text{sec} - (-3^\circ/\text{sec})}{3\text{sec}} = 2^\circ/\text{sec}^2.$$

For an occupant 20 m from the center of gravity, this produces a tangential acceleration of:

$$a_t = \alpha r = \left(2^\circ/\text{sec}^2 \times \frac{\pi}{180} \text{rad/deg}\right) \cdot 20\text{m} = 0.70\text{m/s}^2 = 7/100g.$$

During the transition where the pitch angular velocity changes from upward to downward, an occupant at the aft end of the aircraft would have the reaction force at the feet increased by 7/100 g, and the pilots at the fore end of the aircraft would experience a reduction of 7/100 g.

For most experimenters this additional tangential acceleration is not critical because data are not gathered during the transitions between g levels. In addition, if such data are gathered, they are usually analyzed using the instantaneous g level measured by an accelerometer, so these small fluctuations can be accounted for.

3. Vestibular stimulation during parabolic flight

The vestibular system, located in the inner ear, contains organs to measure three-dimensional motion of the head in space, and is necessary for maintenance of proper balance and generation of compensatory eye movements that stabilize vision despite head and body motion. The semicircular canals sense angular velocity, while the otolith organs sense gravito-inertial acceleration (g level) due to either gravity or linear acceleration. While the otoliths have the dominant role, the body also contains other non-vestibular gravity sensors (graviceptors) that function analogously, such as proprioception. In this section we derive the accelerations and angular velocities sensed by these organs during parabolic flight, which lead to subjective sensations of orientation and motion.

The otolith organ can be modeled as a simple spring-damper-mass system (Figure 4). A mass, the otoconia, embedded in a gelatinous membrane, is attached to the end of a set of lever arms, known as hair cells. The other ends of the hair cells are attached to the temporal bone of the head. Any acceleration of the head causes the hair cells to deflect relative to the temporal bone. (This describes a simplified and idealized set of hair cells, since there are many of them, with a wide range of directional sensitivities.) The hair cells transduce acceleration by measuring the relative movement of the otoconia, and send this information to the brain via the vestibular nerve. The otolith organs are the dominant gravity sensors; the description below applies similarly to other graviceptors [5].

We assume that the temporal bone moves with the rest of the body, and thus experiences the same accelerations as the body (and the aircraft), and that the head is upright with respect to the aircraft so that the head pitch angle with respect to earth is the same as that for the aircraft:

$$a_x = g \cdot \sin\theta$$

$$a_z = \begin{cases} (1.8 - \cos\theta)g & \text{for } 1.8 g \\ g \cdot \cos\theta & \text{for } 0 g. \end{cases}$$

A force is applied to the otoconia due to their weight, $W_O = g \cdot m_O$, which in the vertical direction causes an acceleration a_{Oz} :

$$\sum F_{Oz} = m_O \cdot a_{Oz} = W_{Oz} = W_O \cdot \cos\theta = m_O \cdot g \cdot \cos\theta$$

$$a_{Oz} = g \cdot \cos\theta,$$

and in the longitudinal direction an acceleration a_{Ox} :

$$\sum F_{Ox} = m_O \cdot a_{Ox} = W_{Ox} = W_O \cdot \sin\theta = m_O \cdot g \cdot \sin\theta$$

$$a_{Ox} = g \cdot \sin\theta.$$

The difference in acceleration between the temporal bone a and otoconia a_O , which produces a deflection of the hair cells that is transduced and processed by the brain, is:

$$\begin{aligned}
 a_x - a_{ox} &= g \cdot \sin\theta - g \cdot \sin\theta = 0 \\
 a_z - a_{oz} &= \begin{cases} (1.8 - \cos\theta)g - g \cdot \cos\theta = 1.8g & \text{for } 1.8g \\ g \cdot \cos\theta - g \cdot \cos\theta = 0g & \text{for } 0g. \end{cases}
 \end{aligned}$$

Thus, despite the tilt of the occupant relative to the earth (terrestrial gravity vector), the hair cells sense no fore-aft (x-axis) acceleration. In the vertical (z) direction the hair cells sense the GIA despite the varying normal force of the aircraft on the occupant.

As derived in the previous section, during parabolas there is a near-constant pitch angular velocity of approximately 3 °/sec. This is barely at the threshold of detection of the semicircular canals, the vestibular organs that measure angular rotation of the head [6], and so this rotation is not typically perceived by the occupants.

4. Aircraft dynamics and flight control

4.1 Aircraft dynamics

The control inputs required by the pilots of a parabolic flight aircraft are relatively simple, although precision is required to make the 0 g phase as close to freefall as possible, and care is required not to exceed the load limits of the aircraft which at times flies near its maximum rated speed. The pilots modulate lift L with the elevators and wings, which indirectly changes attitude θ , and thrust T with the engines (Figure 5). Drag D varies with airspeed and other factors. Aircraft weight is defined as $P = g \cdot m_p$, where m_p is the mass of the aircraft. We assume that a_x and a_z for the aircraft are the same as for the occupants, which is true when the occupants do not move relative to the aircraft.

For the 1.8 g phase, in the vertical direction:

$$\begin{aligned}
 L - P_z &= L - P \cos\theta = m_p a_z = m_p (1.8 - \cos\theta)g \\
 L &= P \cos\theta + m_p (1.8 - \cos\theta)g = P(\cos\theta + 1.8 - \cos\theta) = 1.8P \\
 L &= 1.8P.
 \end{aligned}$$

In other words, a constant lift is held throughout the 1.8 g phase, regardless of changes in pitch.

For the 0 g phase, in the vertical direction:

$$\begin{aligned}
 L - P_z &= L - P \cos\theta = m_p a_z = m_p (-\cos\theta)g \\
 L &= P \cos\theta + m_p (-\cos\theta)g = P(\cos\theta - \cos\theta) = 0P \\
 L &= 0P.
 \end{aligned}$$

As with 1.8 g, a constant lift is held throughout the 0 g phase, even during pitch changes.

When airspeed decreases near the top of the parabola, the effectiveness of the wings decreases, and more deflection of the elevators is required to produce the same lift. This increased elevator deflection increases aerodynamic drag. Thrust T must be modulated to counter drag and maintain the parabolic profile. In the longitudinal direction, the desired acceleration is a_x :

$$\begin{aligned}
 T - D - P_x &= m_p a_x \\
 T - D - P \sin \theta &= m_p (g \sin \theta) \\
 T - D - P \sin \theta &= P \sin \theta \\
 T - D &= 0 \\
 T &= D.
 \end{aligned}$$

In other words, thrust counters drag, which varies approximately as the square of airspeed.

The pitch angle of the aircraft is not directly controlled by the pilots, but is a secondary result of other control inputs. During level flight the wings produce an upward lift, while the tail-mounted elevators produce a small downward component of lift in order to maintain a desired pitch angle. When flight conditions change, such as when the pilots deflect the elevators down during freefall, the relative forces from these two surfaces change. Since their moment arms are different, this causes a shift in the center of lift so that it no longer coincides with the aircraft center of gravity, resulting in a torque that causes a pitch rotation of the aircraft.

4.2 Actual Flight Characteristics

Various government organizations have parabolic flight programs for astronaut training and scientific research, and two corporations also make parabolic flight available to customers (Table 1).

Figure 6 shows an example of the g levels experienced during two parabolas in the NASA C-9B. The flight characteristics required to produce these g levels are as follows. The C-9 begins the parabola by accelerating to 350 knots indicated airspeed (KT IAS) while level around 24000 ft (7300 m). This is equivalent to 510 knots true airspeed (KT TAS), 265 m/s or Mach 0.83. (Indicated airspeeds and pitch angles provided by NASA Aircraft Commander Terry Pappas, Personal Communication, April 19, 2006. When making computations based on airspeed, indicated airspeed is adjusted for ambient pressure, and is used for calculations involving aerodynamics such as wing lift. True airspeed is the scalar speed of the aircraft relative to the surrounding air mass, and is used for calculations such as g level.) After the aircraft reaches this maximum speed, a slow climb is initiated while at full thrust to produce vertical speed without reducing airspeed, producing a g level of approximately 1.5 g. Next, a steeper climb further increases vertical velocity and pitch angle, while reducing airspeed, producing a g level of approximately 1.8 g. As pitch angle increases there is a small aftward acceleration (typically less than 0.2 g) of the occupants because the aircraft's longitudinal acceleration is larger than the component of gravity in this direction. At approximately 225 KT IAS (360 KT TAS, 185 m/s, Mach 0.61), when the aircraft is pitched nose-up 45°, the pilots commence the 0 g parabola. They push forward on the control yoke ("push over") to lower the angle of attack of the wings, which reduces wing lift, and simultaneously reduce power to a level just sufficient to overcome drag. At this point the aircraft's movement approximates that of a ballistic mass rather than that of an aerodynamic craft. The airspeed when the aircraft reaches the top of the parabola, at approximately 34000 ft (10000 m), is 140 KT IAS (245 KT TAS, 130 m/s, Mach 0.43). This is approximately 20 KT below the unaccelerated stall speed of the aircraft, the speed below which the wings cease to produce lift in 1 g flight, because as speed decreases the required angle of attack increases, causing separation of the airflow from the wing. The actual stall speed is equal to the unaccelerated stall speed scaled by the square root of the load factor (load supported by the wings divided by total aircraft weight), which means that in 0 g a stall does not occur at any speed since the wings are not supporting any weight. However, in an abort situation a parabola could not be halted and level flight entered until the downward portion of the parabola had started and the aircraft had sufficient airspeed to produce lift. After 25 seconds, at the end of the parabola,

when the nose is pitched down 45° and airspeed is close to 350 KT IAS, the pilots pull up (pull back on the control yoke) and increase thrust to change the aircraft's downward velocity into upward velocity, and restart the cycle. Typically, a set of 10 parabolas is performed in sequence, followed by a 180° turn, and this is repeated four times for a total of 40 parabolas.

An interesting question is what criteria determine and constrain the amount of time spent in freefall. The most important criterion is the earth-vertical component of airspeed at push-over, which is calculated as $V_v = V \cdot \sin(\theta)$. Thus, to increase the earth-vertical component of airspeed, either the total airspeed can be increased, or the pitch angle of the aircraft can be increased. As described above for the C-9B, at push-over the airspeed is 360 KT TAS and the nose is pitched up 45° , which means that vertical speed is 255 KT TAS or 185 m/s. The total airspeed is dependent on the airspeed at the bottom of the trajectory and the loss of airspeed during the pull up. Increasing airspeed at the bottom of the trajectory is not possible since the aircraft is near its maximum airspeed at this point, which is set by structural limitations as a subsonic aircraft approaches the speed of sound. The loss of airspeed during pull-up is dependent on the thrust limits of the engines and the rate at which the pitch angle changes. With a more aggressive pull-up, the pitch angle could be changed in less time and with less altitude gain, so that the total airspeed and the pitch angle would be higher at the push-over transition to 0 g. However, this would increase the loading on the aircraft and thus the occupants. The aircraft structural limit is $+2.5 g$ so some additional loading is possible. For occupants, the g level would be larger, and would be oriented at an angle to the floor, with an increased aftward longitudinal component just before the start of the parabola. This would impose additional safety risks and requirements. Another criterion is the altitude range of the aircraft. Since distance traveled in freefall is proportional to the square of time, each additional second would require a disproportionate increase in altitude excursion. Although airspeed is likely to be the limiting factor in subsonic aircraft, other considerations are the aircraft ceiling and the repetitive stress on the fuselage from changing air pressure.

Summary

Aircraft flying parabolic trajectories have provided an important stepping stone in space exploration and research for the past 50 years. This simple idea took a few years to perfect, and is now routinely used to produce repeated periods of freefall. The trajectory starts with a climb, and halfway through the climb, lift and thrust are reduced to produce approximately 25 seconds of 0 g. During 0 g the plane reaches a plateau and begins to descend. Partway through the descent, lift and thrust are increased, resulting in 1.8 g for approximately 40 seconds. The parabolic trajectory is designed so that the aircraft generates exactly the right amount of lift and thrust to produce the appropriate accelerations along the aircraft vertical (z) and longitudinal (x) axis, respectively, despite pitching relative to the earth. Along the z-axis (aircraft vertical), the sum of the reaction force of the aircraft on the occupant and the weight of the occupant produces a net g level of 0 g or 1.8 g. Along the x-axis (longitudinal aircraft axis), there is a component of occupant weight ($a_x = g \cdot \sin\theta$) that would cause the occupant to slide forward or backward relative to the fuselage. Thrust is modulated so that aircraft acceleration along the x-axis matches the occupant's acceleration, and thus the occupant does not move relative to the airplane. Graviceptors in the body measure the difference between their weight and the net reaction force of the aircraft applied through the occupant's body. Along the z-axis, this difference is 1.8 g and 0 g during the two phases of flight. Along the x-axis the aircraft's acceleration cancels the component of weight acting in that direction. Pitch angular velocity of the aircraft is less than $3^\circ/\text{sec}$, barely at the human threshold of detection. Thus despite the aircraft's large changes in pitch angle relative to the earth, the occupants of the aircraft experience a changing g level along their vertical axis (perpendicular to the floor of the aircraft), with a barely perceptible rotation.

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Figure 1.

Trajectory flown during parabolic flight. The aircraft starts by accelerating to gain velocity before pulling up to convert horizontal velocity into vertical velocity. During the pull-up the g level increases. When a sufficient upward velocity is achieved, the pilots "push-over" (see text) and reduce thrust so that the aircraft and occupants fall together. At the end of the parabola the pilots pull up the g level increases again. The cycle is then repeated.

Figure 2.
Mercury astronauts training during parabolic flight aboard a C-131B in 1959. (Image courtesy NASA, image GPN-2002-000039)

Figure 3.
Coordinate system for the aircraft and free-body diagram of forces on the occupant

Figure 4.
Relative acceleration of the otoliths compared to the head of the occupant

Figure 5.
Forces applied to the aircraft

Figure 6.

Actual g levels on the NASA "Weightless Wonder" C-9B during parabolic flight, along the vertical (z), longitudinal (x), and lateral (y) axes of the aircraft. The altitude is an approximation (derived from accelerometer recordings) for demonstration only and not based on altimeter data. Changes in net gravito-inertial acceleration (GIA) occur overwhelmingly along the aircraft vertical axis, even when the aircraft vertical is not aligned with Earth's gravity. There is a small aftward increase in longitudinal g level near the end of the 1.8 g phase, which is the longitudinal component of gravity as the aircraft pitches up. The pilots could eliminate it by reducing thrust and allowing the aircraft to decelerate, but this would reduce airspeed and thus the time in 0 g.

Table 1

Parabolic flight programs

Organization	Aircraft	Location	Comments
U.S. Air Force	F-94 (single jet)	Wright-Patterson	Early 1950s
	C-131B (twin propeller)	Air Force Base, Ohio	Late 1950s
NASA Reduced Gravity Office	"Weightless Wonder"	Houston, Texas	Last flight in 2004
	Boeing KC-135A (four-engine jet)	Cleveland, Ohio	
	Douglas C-9B	Houston, Texas	Current aircraft
	(twin-engine jet)	Cleveland, Ohio	
Russian Space Agency	Ilyushin IL-76 (four-engine jet)	Star City, Russia	
European Space Agency	"Zero-G" Airbus A300 (twin jet)	Bordeaux, France	
Canadian Space Agency	Dassault Falcon 20 (twin-engine business jet)	Ottawa, Canada	Since 1993
Zero Gravity Corporation	Boeing 727 (twin-engine jet)	Las Vegas KSC, Florida	
Space Adventures	Ilyushin IL-76 (four-engine jet)		Contracts to the Russian Space Agency