# Artificial Gravity in Space


High School Senior

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# Chapter 1

# Introduction

In the following, it will be shown how the idea for the subject selection of the "artificial gravity in space" was developed.

At the Open House of the DLR (German Aerospace Center) in Cologne (Germany), there was the opportunity to see the ISS (International Space Station) training modules from inside and outside. Another very interesting station was the current research work in the DLR Institute of Aerospace Medicine.

In a short-arm human centrifuge (in the DLR laboratory envihab → "**envi**ronment" and "**hab**itat"= habitat), the influence of artificial gravity on the sleep behavior and thus the health of astronauts is being investigated as part of an international study. This study called AGBRESA (**A**rtificial **G**ravity **B**ed **Re**st **S**tudy **A**nalysis) [1] investigates effects that lead to a series of physiological changes such as the degradation of muscles and bones as well as the shift of body fluids towards the head of the astronauts due to the absence of gravity in space, and as a result the cardiovascular system is affected and changes in the eye can take place.

Obviously, weightlessness in space also has disadvantages that can affect the physical and psychological constitution of astronauts during long-term stays. Some of these disadvantages - such as muscle atrophy and calcium depletion in the skeleton - are counteracted by regular exercise (approx. 2,5 hours daily). Therefore, it is obvious that for longer stays in space, the simulation of earth-like environmental conditions by means of artificial gravity can considerably facilitate the stay under such conditions.

Preliminary investigations for this are being carried out in AGBRESA. This first joint long-term bed rest study is taking place in cooperation with DLR, ESA (European Space Agency), NASA (National Aeronautics and Space Administration) and BMWi (German Federal Ministry for Economic Affairs and Energy). For the first time, the use of artificial gravity as a possible measure against the negative effects of weightlessness on the human organism is being deeply investigated.

According to Newton's law of gravitation, gravity is described by two existing masses and their interaction with each other. Consequently, an attractive force acts between the masses $m_1$ and $m_2$, which is directly proportional to each of the masses $m_1$ and $m_2$ and indirectly proportional (proportional to the reciprocal value) to the square of their distance $r$ to each other:

$$\vec{F}_G = -\gamma \cdot \frac{m_1 m_2}{r^2}$$
$$\gamma = 6,6743 \cdot 10^{-11} \left[\frac{m^3}{kg \cdot s^2}\right], gravitational\ constant \qquad \textbf{1}$$

The direction vector of $\vec{F}$ is antiparallel to the distance and its force field is radial $[Fig: 4.1]$. The gravitational force $\vec{F}_G$ on a specimen of mass $m_p$ ($m_2$, e.g. human) under the influence of mass $M_E$ ($m_1$, e.g. Earth) is determined by:

$$\vec{F}_G = -\gamma \cdot \frac{M_E}{{r_E}^2} \cdot m_p \qquad \textbf{2}$$

$Mass\ of\ Earth\ M_E = 5,9723 \cdot 10^{24}\ [kg]$
$Distance\ of\ bodies\ r_E = 6371 \cdot 10^3\ [m], (Earth\ radius)$

With the second Newtonian axiom (law of motion):

> ***If a force acts on a body, it is accelerated in the direction of the force. The acceleration is directly proportional to the force and indirectly proportional to the mass of the body***

and thus, the application of the basic equation of mechanics is valid:

$$F = m_p \cdot a \qquad \textbf{3}$$

and it results the gravitational acceleration $g$ on earth's surface, which a sample of the mass $m_p$ experiences there constantly:

$$m_p \cdot g = m_p \cdot \left(-\gamma \cdot \frac{M_E}{{r_E}^2}\right) \quad \longrightarrow \quad g = 9,81 \left[\frac{m}{s^2}\right] \qquad \textbf{4}$$

According to Albert Einstein, a gravitational field is equivalent to a constantly accelerated frame of reference (equivalence principle of the GR (general theory of relativity)) [2]. Therefore, it is conceivable to generate artificial gravity with the help of a rotating, constantly accelerated frame of reference. Such a system could be helpful for space stations or even spaceships for interplanetary journeys (e.g. missions to Mars).

The gravitational acceleration $g$ of the gravitational field determined in eq. **4** must therefore be generated in the planned rotating frame of reference "space station" (in the following also called "habitat"), by the value of the centrifugal acceleration $a_{cf}$:

$$F_{cf} = m_A \cdot a_{cf} = m_A \cdot \omega_H^2 \cdot r_H \qquad \textbf{5}$$

$F_{cf}$= Centrifugal force,
$a_{cf}$ = centrifugal acceleration,
$m_A$ = Mass of Astronaut,
$\omega_H$= Angular velocity of the habitat,
$r_H$ = Radius of the habitat (outer living area of space station).

The physical features of such a rotating frame of reference are being examined in more detail in the following chapters.

# Chapter 2

# Concepts and current state of the art of space stations

First very thought-out and visionary concepts of a manned space station were already known by the Austrian-Croatian space explorer Herman Potočnik (alias Herman Noordung, 1892-1929). He proposed a wheel-shaped rotating space station as a solution in his book "The Problem of Traveling in Space - The Rocket Engine". This book was published in 1929 and his ideas were taken up again in the 1950's by Wernher von Braun, who incorporated them into his study. NASA considered Potočnik's book as highly valuable and has published a translated and commented version of it in 1995 [3] Both designs have the shape of a wheel with a central rotation axis. From this, one can conclude that by rotation around this axis and thus in the outer area, an artificial gravity is to be generated by centrifugal forces.

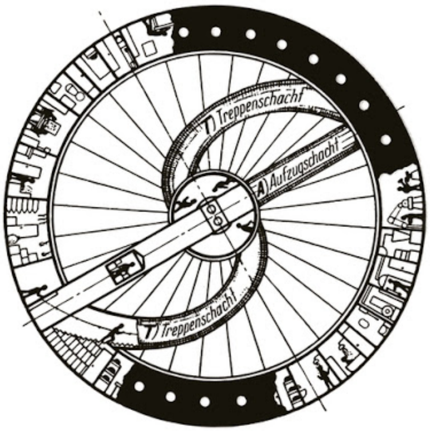


**Figure 2.1:** *The residential wheel 1929, Herman Potočnik [4].*

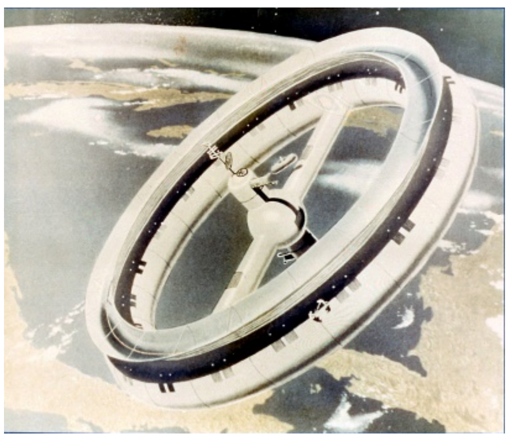

**Figure 2.2:** *Von Braun's space station 1952 [5].*

Potočnik proposed a residential wheel braced with spokes **[Fig.: 2.1]**, as well as two additional ascents of various shapes (radial and spiral), starting from the center to the outer ring. The model of Braun **[Fig.: 2.2]** provides only a straight, radial ascent. Considering the apparent forces occurring in a rotating frame of reference (here especially the Coriolis force), spiral spokes for a convenient transition from the center of rotation to the outer ring area of a space station make sense. This will be explained in more detail in chapter 4.2.2.

The present state of the art in space and orbital stations is currently provided by the ISS. This international space station consists of modular research modules from different nations. The entire space station is weightless in all areas (micro-gravity). The power supply is provided by solar energy. The space station (span $109m$, **[Fig.: 2.3]**) would fill a soccer field in terms of its size.

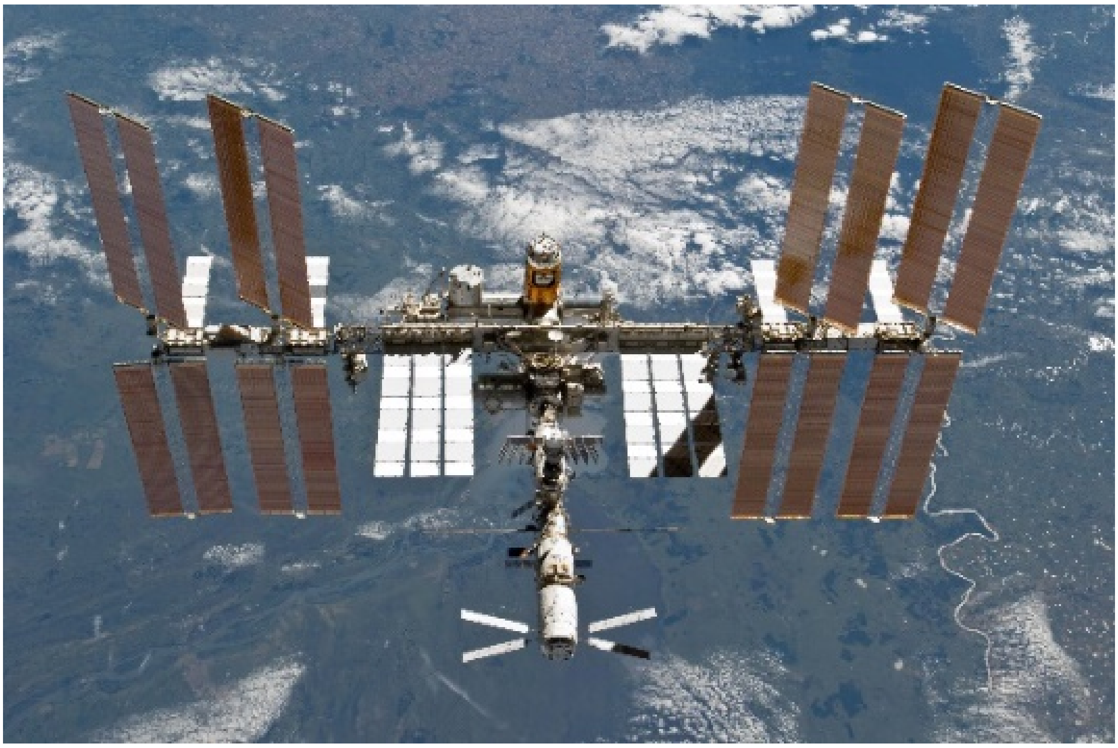

**Figure 2.3:** *The International Space Station (ISS) [6]*

# Chapter 3

# Requirements for future space stations and interplanetary spacecraft

Since humans are not under zero gravity in their natural habitat (Earth) in space, certain precautions must be taken to maintain the physical fitness and health of astronauts, especially for long-term stays in space. In this context, the non-existent gravity is a major problem. In particular, the long-term influence of the absence of gravity on bodily fluids in the brain or the organ of equilibrium are in the narrow field of investigation of the researchers. Muscle atrophy can be counteracted easily by intensive physical training - the disadvantage of those necessary exercises is, that they are very time consuming (up to 2.5h a day). There would be less time remaining for valuable and expensive research work.

Further problems occur at greater distance to the Earth and thus outside the protective Earth magnetic field. The "hard" particle radiation of the Sun (high-energy protons emitted by solar flares), damages tissue and cell DNA. To prevent this, it must be tried to arrange living conditions in space as similar as possible to Earth. I.e., one must possibly also try to produce artificial magnetic fields for the protection against the hard radiation of the sun, building up shelters as well as artificial gravity for more earth-similar living conditions.

Those technical solutions are equally applicable for space stations and spaceships. Space stations in "low orbit" (ISS at approximately 400 $km$ above the Earth) are partly still protected against the hard particle radiation from solar flares by the still existing remanent Earth magnetic field. If one goes on interplanetary journeys (within the solar system, between the planets) like e.g. on mission to Mars (shortest possible travel time with most favorable constellation on the orbits of Earth and

Mars approx. 9 months - however only every 2 years), then must be thought also about shelters and artificial magnetic fields for the defense against the high-energy particle radiation from Sun. Mars does not have a magnetic field to protect humans against radiation. Explorers will have to be responsible for their own safety.

## 3.1 Space stations

As already indicated, a space station should be a habitat (living quarters) with earth-like conditions. This also includes shelters with passive or active mechanisms for defense against hard interstellar particle radiation. By passive mechanisms are meant thick walls for absorption of the particle energy, whereas an active protection against the radiation could be applied by a combination of electric (positive electric field for deflection of the high-energy protons) and magnetic fields (magnitude of the Earth's magnetic field by simulation with current-carrying conductor systems).

Gravity can be replaced via rotation by the resulting centrifugal force (equivalence principle of GR). In the outer area of the rotating station would be the so-called habitat (living area) under artificial gravity (centrifugal force) and in the rotation axis would be the weightless area for conducting research under micro gravity as well as the docking area for supply ships. Special auxiliary drives in the external area could be used to rotate or decelerate the station and drives in the axial area could be used for course corrections in orbit or evasive maneuver to avoid collision with space debris. A space station could look like the one shown in Chapter 3.2 **[Fig.: 3.1]**. This concept is taken up in chapter 4.1 and calculations are made for it.

## 3.2 Interplanetary spacecraft

An interplanetary spacecraft could be designed in exactly the same way as the space station described in **[Fig.: 3.1]**. The structures in the figures below are scaled to each other. The axial area should have a diameter of $10m$ in order to have enough space for the laboratories in weightlessness and to allow the docking of supply spaceships and/or propulsion sections.

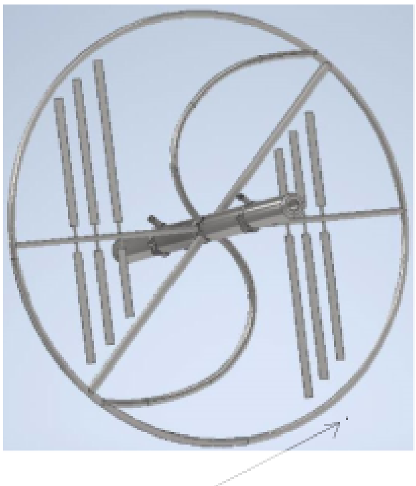

**Figure 3.1:** *Concept of a space station and size comparison with human [source: Linus Hoffmann]*

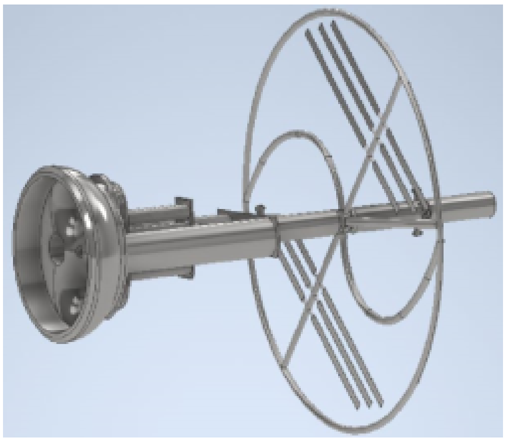

**Figure 3.2:** *Concept of an interplanetary spaceship with modular propulsion section [source: Linus Hoffmann]*

For interplanetary travel, the main propulsion system in the center of the rotating station could be equipped with a modular propulsion and refueling section **[Fig.: 3.2]**.

# Chapter 4

# Physical principles for space station with artificial gravity

As already mentioned at the beginning in the introduction, due to the equivalence principle of the GR in physics [2] it has to be stated first:

***It is impossible to distinguish between the effects of an accelerated motion and the effects of a gravitational field (gravity acceleration). Heavy and inertial mass are not distinguishable.***

It applies:

***Gravitational and inertial forces on small scales of distance and time are the same in the sense that they cannot be distinguished by their effects by mechanical or any other observations[2].***

The mentioned "small distances and time scales" refer to a homogeneous gravitational field (almost everywhere uniform in both magnitude and direction). Of course, when considering large distances, the gravitational field of the earth is a radial field and becomes weaker with the distance (lower field line density). In first approximation, however, it may be regarded as homogeneous at small distances (e.g., geometrical extent of the orbital station ISS with a span of about $109m$ at low earth orbit at an altitude of about $400km$ [6]). One would be in a constant high orbit exactly like on the earth surface in the gravitational field on an equipotential line **[Fig.: 4.1]**. Thus, the equivalence principle **[Fig.: 4.2]** of the GR would be applicable here.

To illustrate this principle, imagine a windowless room in which one is located.

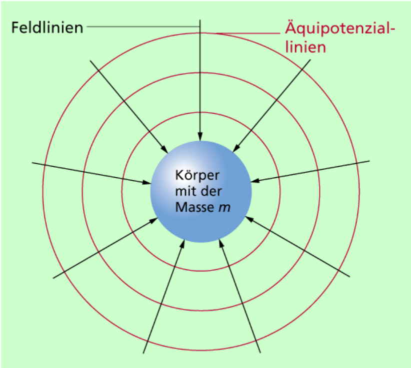


**Figure 4.1:** *Equipotential lines of gravitational field [7].*

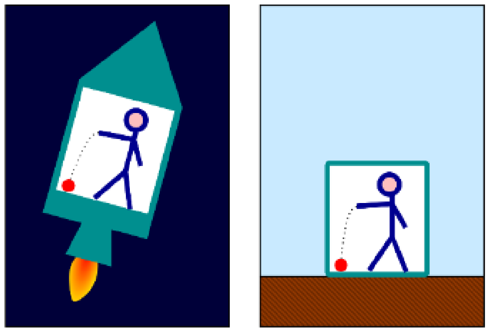

**Figure 4.2:** *Principle of equivalence of the general theory of relativity [8].*

At the same acceleration, it cannot be determined whether this space is in the gravitational field of a planet (**[Fig.: 4.2]**, right) or inside of an accelerated rocket as depicted in (**[Fig.: 4.2]**, left).

## 4.1 Geometric structure

The radius of the station is proposed to be $R_H$ =170$m$ [9]. This corresponds to a somewhat larger extension than the ISS and could be considered technically feasible. The tube diameters in the outer habitat (circular structure) and the different spoke systems (4 x straight and 2 x spiral, see **[Fig.: 3.1]**) should have a diameter of about 5$m$ each (just like the laboratory modules of the ISS [10]) - no further expensive re-design would be necessary.

Size examples of the ISS modules:
Columbus module (European Research Laboratory) of the ISS, outer diameter: 4,477$m$ (diameter incl. micrometeorite shield of 13$cm$ thickness made of several layers of aluminum and KEVLAR resp. NEXTEL (ceramic textile fabric)). The inner diameter is 4,215$m$.

The exact shape of the spiral-shaped "Coriolis ascent" corresponds mathematically to a logarithmic spiral function and should be designed to match the average speed of motion of the habitat's residents. Both directly adjacent, straight spokes should enable freight elevators for the transport of heavy objects from the weightless docking area into the outer habitat located under gravity or vice versa.

Two additional radial spokes will be used to mount the solar panels with simultaneous access hatches for maintenance and/or space walks (extravehicular activities, also known as EVA).

The station represents a rotating torus around an axis located in its center. This axis area is in an almost gravity less state - depending on which distance from the virtual axis experiments will be performed - (micro gravity because of a very small radius, see eq. **4**) and represents both the research laboratory and the docking port for supply spacecraft. Before docking, the spacecraft has to synchronize with the rotation of the space station. To convert the space station into an interplanetary spacecraft or to transport it into lunar orbit as a "lunar gateway", main propulsion and propellant tank modules can be attached to this axis.

In order to rotate or decelerate the station, rocket motors are to be installed symmetrically in the outer ring area for the purpose of tangential acceleration. To start turning the space station, there is no electrical drive possible as proposed by Potočnik [3]. It would not be possible to produce a counter force to transfer its rotational energy for initiation of turning the wheel, without fixing the rotational axis to something (there is just empty space around it). Tangential rocket drives are currently the only way to accelerate or decelerate a rotation of such a station.

For necessary corrections in orbit - to avoid collision with space debris or asteroids - rocket thrusters must be attached to the rotation axis in axial direction and perpendicular to it. To avoid gyroscopic effects (chapter 4.2.3), only an axial or parallel displacement of the rotation axis, should be performed for such maneuvers.

## 4.2 Considerations of forces in rotating frame of reference

Since one would be in a rotating reference frame as an astronaut during the artificial generation of gravity by rotation, the relevant forces occurring there, have to be considered since one would be in an accelerated reference frame.

Every rotation or other acceleration of the reference frame leads to the fact that force-free bodies do not always move straight and uniform. This is described by the effect of inertial forces, which are not generated by other bodies, but occur for the observer concerned only by the acceleration of his reference frame.

These inertia forces can result in accelerated translational motion and/or accelerated or non-accelerated rotational motion. Essentially, these are three inertial forces, the centrifugal force, the Coriolis force and the Euler force. The latter is also known as gyroscopic force.

In the following chapters these forces will be explained briefly. To simplify the considerations a little bit, we shall assume a rotating space station with a fixed oriented axis of rotation, spinning with constant angular velocity $\omega$. There are only two inertial forces acting on the observer (astronaut) located in the rotating reference frame. These inertial forces are the centrifugal force directed radially outward and the Coriolis force occurring perpendicularly (transverse to the direction of motion) to it. This will be explained vividly in chapter 4.2.2 with eq. **15** and **[Fig.: 4.4]**.

### 4.2.1 Centrifugal force

Since the uniform circular motion is an accelerated motion, inertial forces occur for an observer located in the rotating frame of reference, which have the opposite direction as the acceleration and are thus directed radially outward. So, it can be stated:

If a reference frame performs a uniform circular motion with angular velocity $\omega$, an observer rotating with the frame of reference will notice that an inertial force of magnitude,

$$F_{cf} = m \cdot r \cdot \omega^2 = \frac{m \cdot v^2}{r}, \qquad \mathbf{6}$$

the acceleration

$$a_{cf} = r \cdot \omega^2 = \frac{v^2}{r} \qquad \mathbf{7}$$

and the angular velocity

$$\omega = \frac{2 \cdot \pi}{T} \qquad \mathbf{8}$$

with

$a_{cf} =$ $centrifugal\ acceleration\ [\frac{m}{s^2}]$
$m = Mass\ of\ observer\ (astronaut)\ [kg]$
$r = Distance\ from\ center\ of\ rotation\ [m]$

$\omega =$ *angular velocity* $[\frac{1}{s}]$

$v =$ *velocity on a circular path* $[\frac{m}{s}]$, *tangential velocity*

$T =$ *circulation period* $[s]$

will be acting. This inertial force is directed radially outward and is called centrifugal force.

To calculate the centrifugal acceleration $a_{cf}$ prevailing on the earth's surface at a certain latitude, one first needs the coordinates of the latitude (e.g. north, High School Herkenrath, Germany): [11].

Latitude: 50°59′16.39″ N decimal: 50,988°

Longitude: 7°11′25.13″ E decimal: 7,190°

Determining for the centrifugal force on the earth are beside the mass $m$ of the moved body, the angular velocity $\omega_E$ of the earth, as well as the geographical latitude with the angle $\varphi = 50{,}988°$ and the distance $r$ necessary. For the determination of the centrifugal acceleration only $\omega_E$ and the distance $r$ ($R_{Herk}$) of the axis of rotation from the present location (Herkenrath) are sufficient according to eq. **7**.

**[Fig.: 4.3]** illustrates how geometric considerations are used to arrive at the distance $R_{Herk}$.

$$a_{cf} = R_{Herk} \cdot \omega^2 = 4950357\ [m] \cdot \left(\frac{2\pi}{60 \cdot 60 \cdot 24}\right)^2 \left[\frac{1}{s^2}\right] = 0,0262 \left[\frac{m}{s^2}\right] \qquad \mathbf{9}$$

The centrifugal acceleration counteracts the gravitational acceleration of the earth. However, a correction of $g$ by the value $a_{cf}$ should not be performed since this would correspond only to a change in the second decimal place. Also, possible mass anomalies in the earth's crust can lie in this range. For this at that time no data had been available for correction. From eq. **7** follows the azimuthal centrifugal acceleration and subsequently the circumferential speed $v_t$ at location of High School Herkenrath on the latitude circle with eq. **10**:

$$a_{cf} = \frac{v_t^2}{r} \rightarrow v_t = \sqrt{R_{Herk} \cdot a_{cf}}$$
$$v_t = \sqrt{4950357[m] \cdot 0,0262 \left[\frac{m}{s^2}\right]} \cdot 3,6 = 1296,5 \left[\frac{km}{h}\right] \qquad \mathbf{10}$$

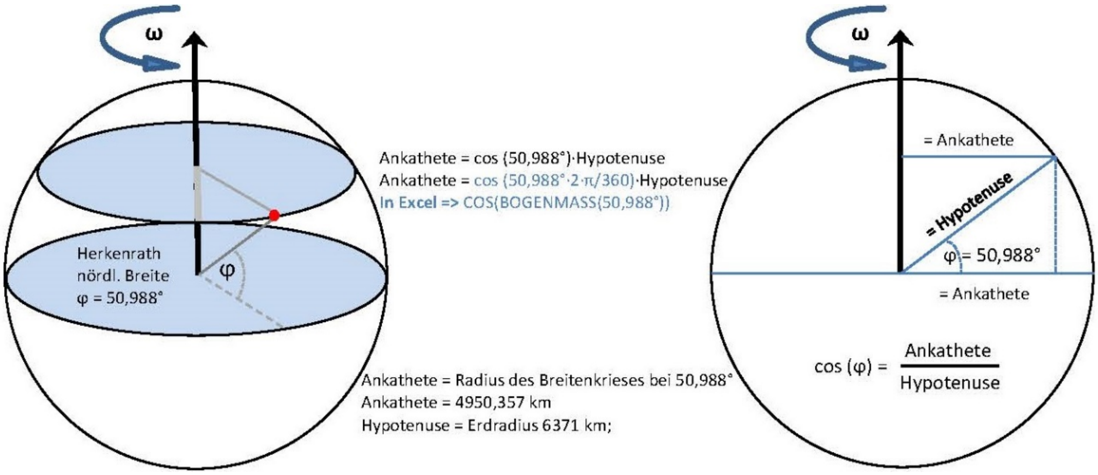


**Figure 4.3:** *Distance from the axis of rotation at the coordinate of northern latitude of Herkenrath High School corresponds to $R_{Herk}$ = 4950,357 km [source: Linus Hoffmann].*

The direction of Earth rotation goes from west to east (looking down from space onto the north pole, counter-clockwise). If we are flying in an aircraft against the direction of rotation (clockwise), e.g. from Europe to the US, with the same amount of tangential speed $v_t$ at twilight, then you can observe the day-night line permanently during the hole flight westbound at supposedly always the same fixed position when looking out of the window.

On a return flight, by utilizing strong tailwinds caused by jet streams (high-altitude winds in an eastbound direction, reaching average speeds of up to 250 km/h), our ground speed – in addition to our airspeed of 850 km/h – would cause us to rush toward the terminator with 1100 km/h - exactly like an opposite-direction aircraft from the east, operating below our flight level. We would have to watch closely for the day-night line as it sweeps quickly past us. Consequently, the night would be shorter for us.

Due to the Earth's rotation, air masses are deflected to the right in the northern hemisphere (ergo the jet-stream is causing a tailwind component moving eastbound) and to the left (westbound) in the southern hemisphere. That phenomenon is being caused by the so called Coriolis force. This will be discussed subsequently.

### 4.2.2 Coriolis Force

Gaspard Gustave de Coriolis (french mathematician and physicist, 1792-1843) found out that in contrast to the two already known apparent forces acting in rotating frame of references, the centrifugal force and the gyroscopic force (Euler force), another apparent force, the Coriolis force is acting. This inertial force acts only on bodies moving relative to the rotating reference frame (e.g., relative to the surface of the earth or to a rotating space station). If a frame of reference performs a uniform circular motion with the angular velocity $\omega$, a co-rotating observer thus finds that on his body of mass $m$, when he moves with a speed $v$ relative to this frame of reference, an inertial force with the magnitude,

$$F_{Cor} = 2 \cdot m \cdot v \cdot \omega = \frac{2 \cdot m \cdot v \cdot 2\pi}{T} = \frac{4\pi \cdot m \cdot v}{T} \qquad \mathbf{11}$$

acts on his body. This force is always acting perpendicular to the axis of rotation and the relative motion of the body on which it acts. The Coriolis force is proportional to the angular velocity $\omega$ of the rotational frame of reference.

The horizontal component of the Coriolis force existing at a specific location (latitude) on Earth (**[4.3]**, left, running in the northern hemisphere, the upper circular disk) is calculated from:

$$F_{Cor} = 2 \cdot m \cdot v \cdot \omega_E \cdot sin(\alpha) \qquad \mathbf{12}$$

with the Coriolis parameter as constant of the uniformly rotating frame of reference:

$$f_{Cor} = 2 \cdot \omega_E \cdot sin(\alpha) \qquad \mathbf{13}$$

it follows,

$$F_{Cor} = m \cdot v \cdot f_{Cor} \qquad \mathbf{14}$$

with

$m = mass\ of\ astronaut\ [kg]$,

$v = speed\ of\ astronaut\ [\frac{m}{s}]$,

$\omega_E = angular\ velocity\ of\ Earth\ (\frac{2\pi}{60*60*24\ [s]} = 7,272 \cdot 10^{-5}\ [\frac{1}{s}])$,

$\alpha = angle\ between\ \vec{v}\ and\ \vec{\omega}$.

The Coriolis force $\vec{F}_{Cor}$ is proportional to the speed of motion, perpendicular to the vector $\vec{v}$ of motion (velocity) and its vector $\vec{\omega}_E$ of earth rotation. Vector $\vec{F}_{Cor}$ thus is resulting from the cross product of the vectors $\vec{v}$ and $\vec{\omega}$.

$$\vec{F}_{Cor} = 2 \cdot m \cdot \vec{v} \times \vec{\omega} \qquad \textbf{15}$$

To illustrate the directions of the vectors, one can use the right-hand rule from **[4.4]**a.

The accelerations resulting from the amount of the Coriolis factor on Earth are very small compared to the space stations rotating with much higher $\omega_H$ to obtain the required centrifugal acceleration of $a_{cf}$ = 9,81 $[\frac{m}{s^2}]$, respectivally $g$.

Let's first assume a radius of the space station's torus (outer ring) that is about three times the dimensions of the current ISS and therefore we may assume that this size is technically feasible. This would be of a station radius of about $R_H$ =170$[m]$. The US-american cardiologist Ashston Graybiel found out within a study that an $\omega_H$ of about 2 to 3 RPM of a rotating space station could be bearable for a longer period of time for astronauts living in such a station [9]. With eq. **7** and eq. **8** then results the circulation period $T$ in that order of magnitude from eq. **17**:

$$9,81[\frac{m}{s^2}] = R_H[m] \cdot \omega_H^2[\frac{1}{s^2}] = 170[m] \cdot \left(\frac{2\pi}{T}\right)^2 \left[\frac{1}{s^2}\right] \qquad \textbf{16}$$

$$T = \sqrt{\frac{170[m] \cdot 4 \cdot \pi^2}{9{,}81[\frac{m}{s^2}]}} = 26,16\ [s] \rightarrow \text{RPM=2,3} \qquad \textbf{17}$$

$$\omega_H = 0,24 \left[\frac{1}{s}\right] \qquad \textbf{18}$$

The spiral-shaped "Coriolis ascent or spoke stairwell" to the habitat **[Fig.: 4.4]** and the Coriolis force acting here in the longitudinal axis of the body during the movement of the astronaut from the axis of rotation to the outside of the habitat, should have the effect, that the astronaut initially pulls himself into the spiral-shaped Coriolis ascent starting from the weightless laboratory on handrails attached on both sides of the ascent tube and at the same time continuing to move on the running surface with his feet. Presumably this is going to happen at first with a speed of approximately $v = 1[\frac{m}{s}]$. According to eq. **12** and with the included angle $\alpha = 90°$ between the vectors $\vec{v}$ and $\vec{\omega}$ and the mass $m$ =90$[kg]$ of the astronaut, a Coriolis force of:

$$F_{Cor} = 2 \cdot 90[kg] \cdot 1 \left[\frac{m}{s}\right] \cdot 0,24 \left[\frac{1}{s}\right] \cdot \sin{(90°)} = 4,32\ [daN] \qquad \textbf{19}$$

will result. The unit used here for the force, Deka Newton $[daN]$, was taken for the sake of illustration, since this corresponds approximately to the weight force in units of $[kg]$.

Moving outward with this velocity from eq.**19**, the astronaut experiences a Coriolis force of 4,32$[daN]$ in the longitudinal axis of the body, i.e., in the plane orthogonal to the direction of the rotational axis of the habitat (red arrow), according to **[Fig.: 4.4]**. Increasingly moving outward, the centrifugal force (blue arrow, chapter 4.3, table 4.3) increases and eventually takes the predominant part. On the way back from the habitat, the Coriolis force points away from the rotation axis and makes the astronaut somewhat heavier.

Another advantage of this spiral ascent is that the Coriolis force during the steadily increasing centrifugal force when moving outward, with its force vector results in a slightly propelling force in the direction of the motion vector (green). Moving from the inside to the outside, the astronaut will have the feeling of moving downhill, becoming heavier. On the way back, this effect would be braking, as if going uphill but getting lighter and lighter. In this way, one achieves a controlled movement in the tube without bumping uncontrollably against the wall of the spoke tube. Within a straight spoke tube, the Coriolis force would push a body onto one side of the wall, and the frictional force then acting would ensure that the rest of the upper body would be pushed outwards due to the centrifugal force (consequence: uncontrolled falling forward).

The Coriolis force results in a reduction of the centrifugal component and thus of the weight force of the astronaut by approx. 4,32$[kg]$ if the velocity (e.g., $v$=1$[\frac{m}{s}]$ against the rotation) in the habitat area remains unchanged. If the astronaut changes the direction of motion in the habitat area (in **[Fig.: 4.4]** thus in the direction of rotation) and keeps his velocity, he will become heavier by approximately 4,32$[kg]$, at higher locomotion velocities correspondingly more (various possibilities of sporty training).

Thus, if one engages in running within the habitat, the physical load depends on the direction of motion (running with or against the rotational motion of the habitat). According to eq. **14**, if the speed is doubled, the Coriolis force would also be doubled. Thus, it can be stated that there are three cases of relative motion to the rotating reference frame, where the Coriolis force acts only in the following first two cases:

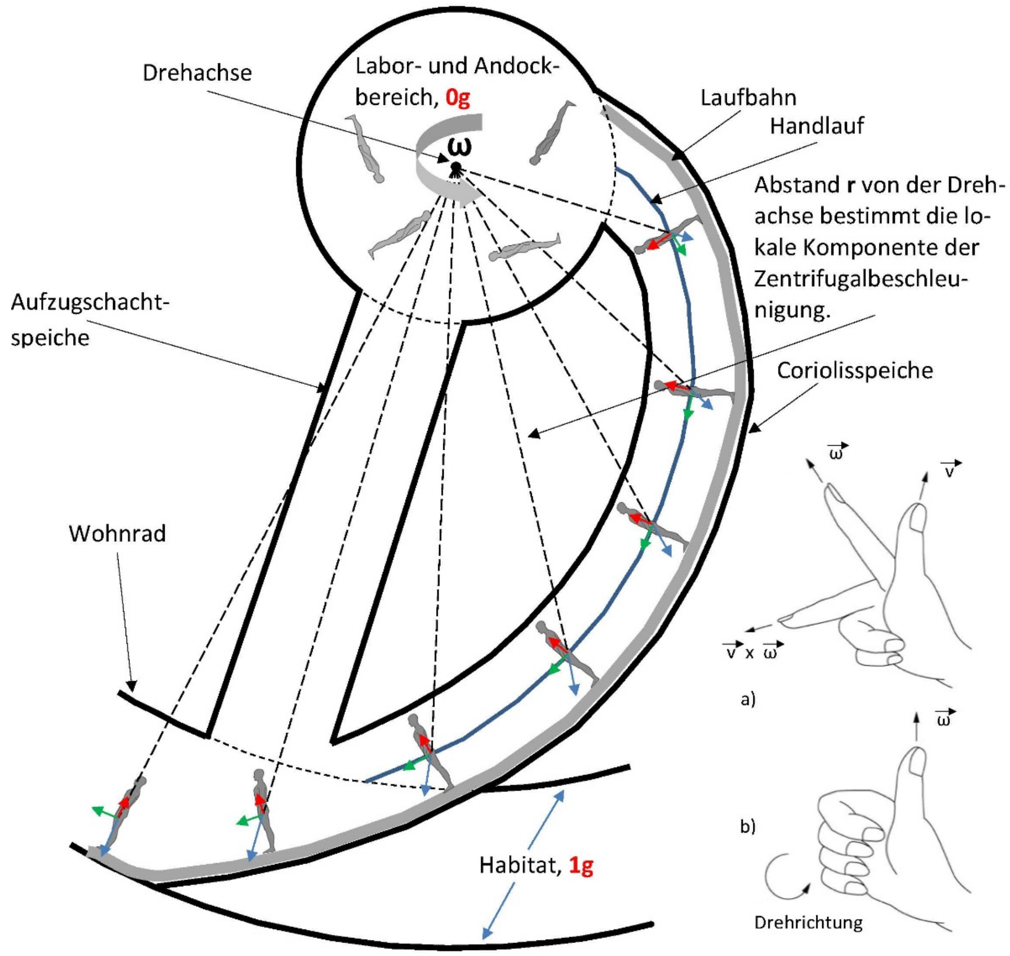


**Figure 4.4:** *The astronaut moves within the spokes stairwell from inside to the outside not on, but in the plane of rotation. The Coriolis force thus acts in the direction of his body's longitudinal axis and does not have a "knock over" effect like on a playground carousel but weakens the "increasing gravity" towards the outside somewhat. Coriolis force (red arrow), speed of motion (green arrow), centrifugal component (blue arrow) [source: Linus Hoffmann]*

*1. <u>case: radial motion</u>*
*In the case of movements on rotating bodies, which go radially outward, this leads to a deflection relative to the rotating base in the opposite direction to the direction of rotation (see right hand rule,* ***[Fig.: 4.4]****a).*

*2. case: tangential motion*
*considering a rotating disk, on which a body moves additionally in the direction of rotation while the distance to the center of rotation remains fixed, the vector calculation (right hand rule* ***[Fig.: 4.4]****a) shows that the Coriolis force also acts to the right in the direction of motion, i.e. outward. To the outside, also the co-rotating observer feels the centrifugal force, i.e., the Coriolis force strengthens here the centrifugal force. If the body moves against the direction of rotation, the centrifugal force is weakened accordingly.*

*3. case: axial motion*
*The body moves along (parallel to) the axis of rotation. In this case, Coriolis force does not occur.*

For a given mass and speed of motion of a specimen (astronaut) in the rotating reference frame, the Coriolis factor is the factor influencing the Coriolis force due to the rotational speed of the frame of reference (space station or Earth):

Coriolis factor on Earth with eq. **13**:

$$f_{Cor,Earth(Herkenrath)} = 2 \cdot \omega_E = 1,45 \cdot 10^{-4}[\frac{1}{s}] \qquad \mathbf{20}$$

Coriolis factor in space station with eq.**18**:

$$f_{Cor,Spacestation} = 2 \cdot \omega_H = 4,80 \cdot 10^{-1}[\frac{1}{s}] \qquad \mathbf{21}$$

The Coriolis force acting on the inhabitants of the habitat is about 3310 times stronger compared to that on the surface of the Earth. Thus the Coriolis factor is representing a direct measure for adverse effects on the human body (extreme nausea and vomiting are to be expected). The greater this factor is, the more disadvantageous it is for the residents. For this reason, it is important to know what this worst-case scenario can do to the human body on long term.

A final consideration on the distribution of Coriolis force and centrifugal force in the assumed habitat (radius $R_H$ =170[$m$]), according to **[Fig.: 4.4]**, is the percent difference of the acting forces. In addition, there was a study conducted in 1965 by Dr. Ashton Graybiel at the Naval Aerospace Medical Institute, commissioned by NASA [9]. Graybiel and her team found that a rotational speed of about 4 revolutions per minute (RPM) is acceptable for most trained people. A NASA guideline for space station designs of 1–2 RPM was derived for the general population without special preparation and largely based on Graybiel's data to ensure that even untrained individuals do not develop symptoms.

If the astronaut is at rest in the outer area of the habitat, the different components of the centrifugal acceleration between head and foot and its effects on the human organism has been and must be further primarily investigated. Coriolis forces would act in radial direction - like centrifugal force - because of the main tangential motion of residents in the habitat (see 2nd case, pp.20).

Differences in centrifugal acceleration for a $h$ =1,85$[m]$ tall person between head and foot (corresponds to an astronaut in an upright position within the habitat) can be easily derived and calculated simply as the $\Delta_{a_{cf}}$ of the centrifugal accelerations by the ratio between the height of the body and the radius of the station as follows:

$$\Delta_{a_{cf}}\% = \frac{a_{cf,Foot} - a_{cf,Head}}{a_{cf,Foot}} = \frac{\omega_H^2 \cdot R_H - \omega_H^2 \cdot (R_H - h)}{\omega_H^2 \cdot R_H} = \frac{h}{R_H}$$

$$\rightarrow \Delta_{a_{cf}}\% = \frac{1,85[m]}{170[m]} = 0,01 = 1\% \qquad \mathbf{22}$$

The actual effects of the differences of centrifugal accelerations between head and foot within the habitat are within the margin of 1% and must be compared experimentally by testing with a centrifuge (for envihab with $r_c$, eq.**23**) on Earth:

$$\Delta^*_{a_{cf}}\% = \frac{h}{r_c} \rightarrow \Delta^*_{a_{cf}}\% = \frac{1,85[m]}{3,80[m]} = 0,49 = 49\% \qquad \mathbf{23}$$

In the *envihab*∗ human centrifuge of the DLR in Cologne **[Fig.: 4.5]**, very high values for the differences of the centrifugal accelerations between head and foot are obtained according to eq.**23**, associated with high Coriolis factors as per eq.**12** and - if there are effects - these can be detected well at very high acceleration values. If the effects on the human body are not critical here, this is even less the case for larger radii of the centrifuge (up to the dimensions of the proposed space station, $R_H$ =170$[m]$).

**Figure 4.5:** *DLR short arm centrifuge of the envihab [12].*

### 4.2.3 Euler force

In classical mechanics, the Euler force (named after Leonhard Euler, 1707, Swiss mathematician and physicist) is:

> ***The apparent force (inertia force) acting on a body that occurs in a rotating frame of reference when the direction of the axis of rotation or its rotational speed changes in time.***

This force is also called gyroscopic force and shall be listed here only for the sake of completeness:

$$\vec{F}_{Euler} = -m \cdot \frac{d\vec{\omega}}{dt} \times \vec{r} = -m \cdot \vec{\alpha} \times \vec{r} \qquad \textbf{24}$$

with

$$the\ angular\ velocity\ \vec{\omega}\ of\ the\ reference\ frame,$$

$$the\ angular\ acceleration\ \vec{\alpha}\ of\ the\ reference\ frame,$$

$$the\ position\ vector\ \vec{r}\ of\ the\ point\ in\ the\ reference\ frame$$

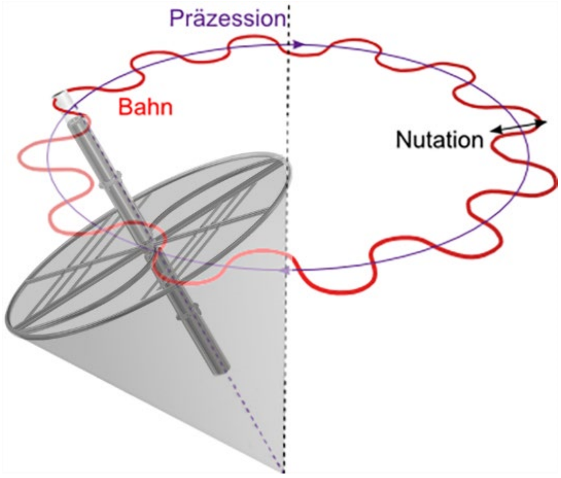


**Figure 4.6:** *Pictorial description of the precession and nutation [13].*

With effect of a tilting moment on the direction of the rotation axis, the axis of a gyroscope (space station) would get into precession (e.g., by wrong docking of a spaceship). A force effect perpendicular to the tilting direction of the rotation axis is shown. The axis then describes a rotation on the mantle of an imaginary cone **[Fig.: 4.6]**. A second possible motion of the gyro axis is nutation (wobbling motion superimposed on the precession). This happens when the angular momentum is not aligned parallel to one of the main inertial axes of the gyro.

Nutation effects can be minimized constructively by a symmetrical mass distribution of the space station to the rotation axis. For preventing precession and nutation, an electrical "shifting mass balance weight" system could help to mitigate such unintended gyroscopic movements.

If the amount of angular velocity changes (e.g. by deceleration of rotation), one can notice that the inertial behavior with respect to rotation depends not only on the mass of a body, but also on its spatial distribution.

The gyroscopic forces shall be disregarded here, because in a rotating frame of reference with constant angular velocity and axis orientation, as well as a symmetrical mass distribution, only the two apparent forces Coriolis- and centrifugal force are acting. Such a station would be able to orbit stably around the earth or the moon with constantly the same axis orientation and rotational speed. Changing mass distributions in the rotating habitat through moving masses like humans or other shifting items of mass, could be compensated through an active mass balancing system with actuator moved counterweights and a sensor systems, measuring accelerations, indicating precession and/or nutation of the gyro "space station".

## 4.3 Calculations for the space station ($R_H$=170[$m$]) in comparison to the earth

The following calculations were performed using the formulas used in this work. A torus for the space station with a radius of 170$m$ was assumed. This size at least gives the prospect of technical feasibility when compared to the current span of the ISS of 109$m$.

The calculations in **[Tab.: 4.1]** show here in the Earth frame of reference that, for example, a teacher moving with the mass of $m$ =90 [$kg$] and a speed of motion

**Table 4.1:** *Coriolis force on moving objects of different masses and velocities on Earth and in the space station.*

| Earth (Area Herkenrath)<br>Coriolis force on moving objects of different masses and speeds.<br>Circulation time $T_{Earth}$ = 86400 [s], $\omega_E$ = 7,27 $\cdot 10^{-5}[\frac{1}{s}]$ | | | | |
|---|---|---|---|---|
| Earth, surface gravitational acceleration<br><br>1g $[\frac{m}{s^2}]$ | Mass<br><br>m[kg] | Speed of motion of the mass $m$ moving perpendicular to the earth axis<br><br>v $[\frac{m}{s}]$ | Coriolis factor<br><br>$f_{Cor\,E}$ $[\frac{1}{s}]$ | Coriolis force<br><br>$F_{Cor\,E}[daN]$ |
| Human 1 | 90 | 1 | 1,45E-04 | 0,0013 |
| Human 2 | 130 | 1 | 1,45E-04 | 0,0019 |
| Tank | 50000 | 1 | 1,45E-04 | 0,7272 |
| Wind ($1m^3$ Air) | 1 | 10 | 1,45E-04 | 0,0001 |
| bullet | 0,02 | 1000 | 1,45E-04 | 0,0003 |
| Space Station<br>Coriolis force on moving objects of different masses and speeds.<br>Circulation time $T_{space\ station}$ = 26,16 [s] $\equiv 2,3\,RPM$, $R_H$ =170 [m],<br>$\omega_H = 0,2402\ [\frac{1}{s}]$, $\alpha(\angle\,\omega, v) = 90°$ | | | | |
| Space Station, outer radius, centrifugal acceleration<br><br>1g $[\frac{m}{s^2}]$ | Mass<br><br>m [kg] | Speed of motion of the mass $m$ perpen- dicular to the earth axis<br><br>v $[\frac{m}{s}]$ | Coriolis factor<br><br>$f_{Cor\,H}[\frac{1}{s}]$ | Coriolis force<br><br>$F_{Cor\,H}[daN]$ |
| Astronaut 1 | 90 | 1 | 4,80E-01 | 4,32 |
| Astronaut 2 | 130 | 1 | 4,80E-01 | 6,24 |
| Air condition ($1m^3$ Air) | 1 | 1 | 4,80E-01 | 0,048 |
| Tank | 50000 | 1 | 4,80E-01 | 2401,83 |

of $v = 1[\frac{m}{s}]$ from the parking lot to the classrooms of High School Herkenrath experiences there a Coriolis force of 0,0013$[daN]$ deflecting laterally to his direction of motion. This corresponds to a weight force of approximately 0,0013$[kg]$.

If the teacher is in a great hurry ($v$ =3[$\frac{m}{s}$]) in order not to be late for class, the lateral deflection already corresponds to 0,0039[$kg$]. Thus, the force is directly proportional to the mass and the velocity of the teacher at constant rotation of the earth.

If a tank with a considerably higher mass of 50 $t$ moves at the same speed mentioned above, the force deflecting it laterally corresponds to a weight force of already 0,727[$kg$].

If we now look at the acting Coriolis forces in the given space station, we see that due to the approx. 3310-fold larger Coriolis factor (see **[Tab.: 4.2]**, below, by means of eqs.**14**, **20**, **21**), the forces also increase by this factor. At $v$ =1[$\frac{m}{s}$], the astronaut experiences a lateral force of 4,32[$daN$], and if there was theoretically a tank up there, it would already experience a lateral deflection of 2,4 $t$ weight force at the same velocity $v$.

**Table 4.2:** *Ratio of Coriolis factors space station/Earth at different habitat radii, starting from envihab* DLR short arm centrifuge with $r_c$=3,80 $[m]$ up to $R_H$. Astronaut lies with feet facing outward, so to say on the outer face of the inside of the habitat tube.*

| Space station/Earth<br>Ratio of Coriolis factors for space station/earth at different habitat radii.<br>$m_{Astronaut} = 90[kg], a_{cf} = 1g\ [\frac{m}{s^2}]$ | | | | | |
|---|---|---|---|---|---|
| Radius Habitat<br>$r_{c\to H}$[m] | Circulation time<br>$T_{c\to H}$ [s] | Circulation speed in habitat (outside)<br>$v_{c\to H}\ [\frac{m}{s}]$ | Coriolis factor station<br>$f_{Cor\,c\to H}[\frac{1}{s}]$ | Coriolis factor Earth<br>$f_{Cor\,E}[\frac{1}{s}]$ | Ratio<br>$\frac{f_{Cor\,c\to H}}{f_{Cor\,E}}[-]$ |
| 3,80* | 3,91 | 6,1 | 3,21 | 1,45E-4 | 28438 |
| | | | | | |
| 42,5 | 13,08 | 20,42 | 9,61E-01 | 1,45E-4 | 8501 |
| 85 | 18,49 | 28,87 | 6,79E-01 | 1,45E-4 | 6011 |
| | | | | | |
| 170 | 26,16 | 40,83 | 4,80E-01 | 1,45E-4 | 3310 |

The calculations (see eqs. **14**, **17**, **18**) in **[Tab.: 4.2]** show the multiplication of the ratio of Coriolis factors between Earth and different rotational frame of references (with different radii) to arrive at the centrifugal acceleration of 1$g$.

It was noticed that the short-arm centrifuge of DLR's envihab* laboratory has the largest Coriolis factor and is thus very well suited for investigations to amplify and thus better detect any effects of these accelerations on the physiognomy of the human body. The calculations in **[Tab.: 4.3]**(see eqs. **6**,**11**, **14** and **18**) show in the frame of reference "space station" an increase of the centrifugal force with increasing distance to the rotation axis.

**Table 4.3:** *Increase of the centrifugal force with increasing distance to the axis of rotation, while an astronaut weighing 90$[kg]$ moves outward with $v$=1$[\frac{m}{s}]$.*

| Space Station<br>Increase in centrifugal acceleration with increasing distance from the axis of rotation. $m_{Astronaut} = 90[kg]$, $v_{Astronaut} = 1[\frac{m}{s}]$, $a_{cf} = 1g[\frac{m}{s^2}]$, $\omega_H = 0,2402[\frac{1}{s}], \alpha(\angle\,\omega, v) = 90°$ | | |
|---|---|---|
| Distance of the outer edge of the habitat to the axis of rotation<br>r [m] | Coriolis force<br>$F_{Cor}[daN]$ | Centrifugal force<br>$F_{cf}[daN]$ |
| 5 | 4,32 | 2,60 |
| 10 | 4,32 | 5,19 |
| 15 | 4,32 | 7,79 |
| 20 | 4,32 | 10,38 |
| 25 | 4,32 | 12,98 |
| 30 | 4,32 | 15,58 |
| 35 | 4,32 | 18,17 |
| 40 | 4,32 | 20,77 |
| 50 | 4,32 | 25,96 |
| 155 | 4,32 | 80,47 |
| 160 | 4,32 | 83,07 |
| 165 | 4,32 | 85,67 |
| 170 | 4,32 | 88,26 |

# Glossary

**AGBRESA** Artificial Gravity Bed Rest Study.

**EVA** Extravehicular Activity.

**GR** Genral Theory of Relativity.

**BMWi** German Federal Ministry for Economics Affairs and Energy.

**DLR** Deutsches Zentrum für Luft und Raumfahrt.

**DNA** Deoxyribonucleic acid.

**envihab** environmental habitat.

**ESA** European Space Agency.

**ISS** International Space Station.

**KEVLAR** registered trademark of DuPont Group.

**NASA** National Aeronautics and Space Administration.

**NEXTEL** registered trademark of US-Group 3M.

**RPM** Revolutions Per Minute.

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