Teaching material 3 (students):

How do tidal forces affect the Earth and the Moon? In the past, today, and in the future. Why is the Moon so important for (human) life on Earth?

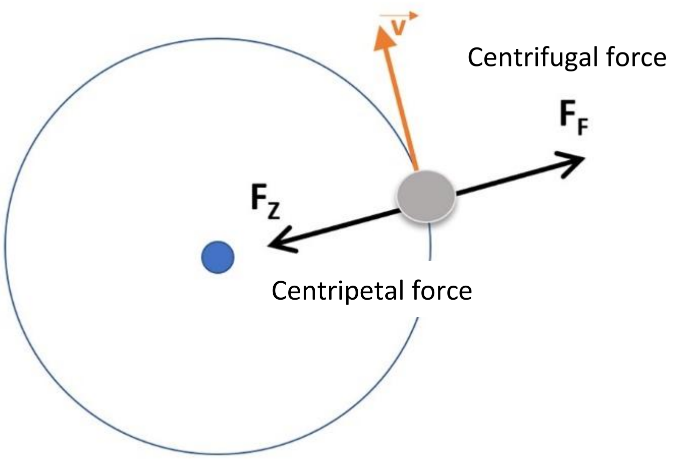
The map content is also integrated into the augmented reality app "Columbus Eye" to view and interact with it.

Apple Store Google Play

*"**The cause of the tides is <u>astronomical</u>, but the reaction of the oceans to them is geographical.**"* – Wolfgang Glebe: Ebbe und Flut – Das Naturphänomen der Gezeiten einfach erklärt (Ebb and Flow – The Natural Phenomenon of the Tides Simply Explained)

Definitions:

- **Centrifugal** force **(FF)** is an inertial force that acts on bodies in rotating reference systems and is always directed outward at right angles to the axis of rotation.
- **Centripetal force (FZ)** is a force directed toward the center that causes circular motion. It is a compelling force, because without it, a body would leave its circular path (e.g., on a string).



Author: Roman Hiby (roman.hiby@rub.de); Contact: Jun. Prof. Dr. Andreas Rienow (andreas.rienow@rub.de)
AG Geomatics – Interdisciplinary Geoinformation Sciences, Institute of Geography, Ruhr-Universität Bochum

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Dear Marie,

I'm spending two weeks at the North Sea. The journey was really exhausting, but now we're finally here and it's worth it. It's so beautiful here and we have perfect weather for swimming. Can you imagine how annoyed I was when I walked to the beach full of anticipation and the water was suddenly gone?! Sure, there are tides, but somehow I didn't think of that at the time.

I then asked myself how tides actually come about and looked it up on the Internet. The phenomenon of tides was apparently a great mystery until modern times and often gave rise to myths and bizarre speculations. Many important Western scholars have grappled with this question, including *Galileo Galilei, Simon Stevin, René Descartes*, and *Johannes Kepler*. It was not until the end of the 17th century that *Isaac Newton* came up with the correct explanation, and another century later, *Pierre Simon de Laplace* developed a further theory that was even more accurate and complex. These are just a few of the important names I found. After that, there were still further developments and revisions of the classical theories. Even today, various explanations are still circulating on the internet. I have often read that these are wrong because they have been oversimplified and are therefore no longer correct. I am confused!

The only thing I know for sure is that the tides have something to do with the Moon's gravitational forces. I can kind of understand the one tidal wave, but why is there one on the opposite side of the Earth, i.e., on the side facing away from the Moon? Can you help me out here?

Have a great
vacation!

Johanna

Author: Roman Hiby (roman.hiby@rub.de); Contact: Jun. Prof. Dr. Andreas Rienow (andreas.rienow@rub.de)
AG Geomatics – Interdisciplinary Geoinformation Sciences, Institute of Geography, Ruhr-Universität Bochum

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1. **Brainstorm why the tides are important and why they should be observed.**

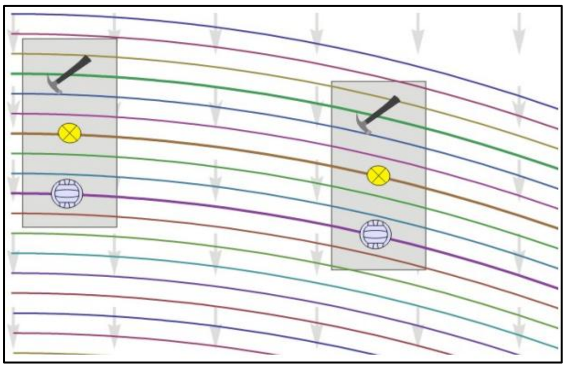
   Write down your thoughts in a mind map. Use the Earth-Moon system in the app to help you.

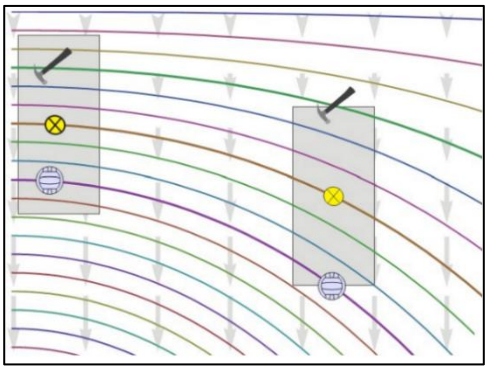
   Compile the results in a plenary session.

2. **Homogeneous vs. inhomogeneous gravitational field**

   Compare the images and add keywords that explain them.

   - The two illustrations show the two different forms of the gravitational field, represented by a box with a hammer and a volleyball, as well as the existing center of gravity.
   - In free fall in a homogeneous gravitational field, there exists weightlessness and mass = 0 (see box below).
   - This relative acceleration of bodies in an inhomogeneous gravitational field is called tidal acceleration. It can be explained as a deviation from weightlessness.
   - The difference between the inhomogeneous and homogeneous gravitational field leads to the relative acceleration of the bodies.
   - Keywords could include: gravity, weightlessness, (in)homogeneous gravitational field, free fall, projectile trajectories





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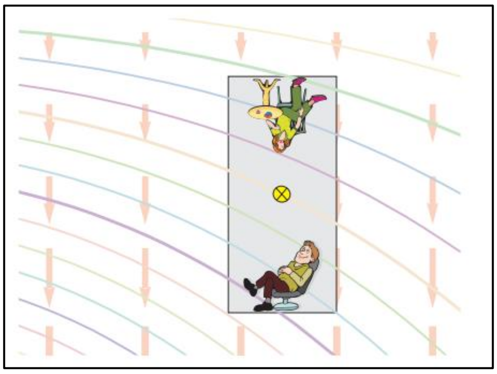
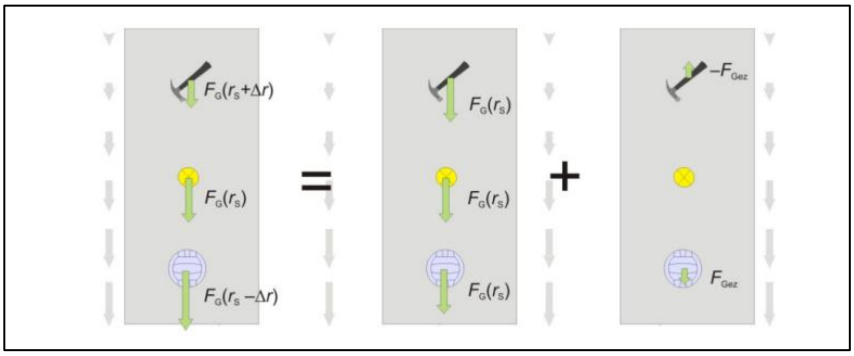
2.1. Determine at which points artificial gravity is acting in this figure.



The box falling in the inhomogeneous gravitational field is the simplest example of the occurrence of tidal forces. Everything essential is already evident here: the fact that the inhomogeneity of the gravitational field is responsible for the ability to generate artificial gravity in this way and that the tidal forces act outward on both sides (two tidal bulges). A characteristic feature is the distance dependence of the tidal force, which decreases with the cube of the distance (and is therefore much stronger than the gravitational force). This explains why the tidal forces of the Sun on Earth are weaker than those of the Moon, even though the gravitational force of the Sun is 178 times greater.



- Left: inhomogeneous gravitational field
- Center: homogeneous gravitational field
- Right: tidal acceleration

In a non-homogeneous gravitational field, different gravitational forces act on an extended body at different locations. Only at the center of gravity of the freely falling body, there is weightlessness. The occurrence of tides is explained by the fact that the rigid body Earth can only accelerate toward the Moon, while the moving parts of water on Earth experience different accelerations depending on their location.

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Compile the results in a plenary session.

2.2. Calculate the position of the center of gravity (Barycenter) of the Earth and the Moon.

In this way, the Moon is constantly falling towards the Earth. However, due to the validity of Newton's third law, the Earth is also falling towards the Moon in an analogous manner. Together, they fall towards their center of gravity (Barycenter), which lies within the Earth. The magnitude of the two gravitational accelerations is inversely proportional to the ratio of the masses of Earth and Moon.

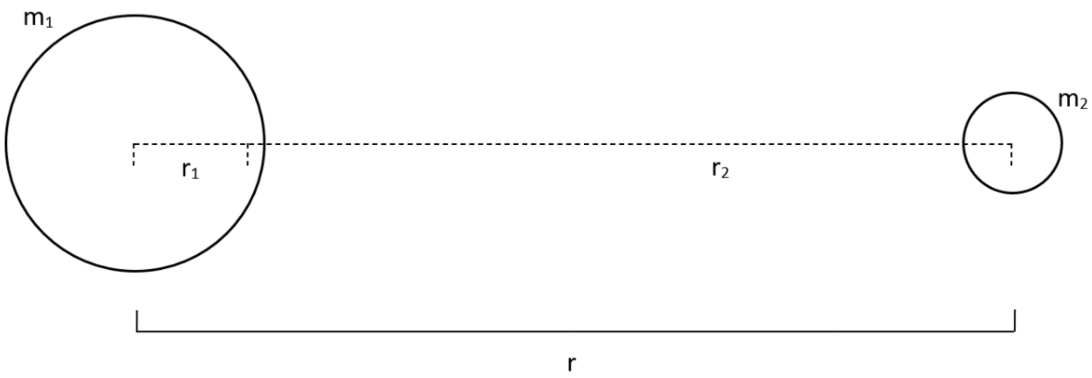

Figure not to scale

r = 384.000 km (average distance between Earth and Moon)

m_1 = 5,972*10^{24} kg (mass of Earth)

m_2 = 7,349*10^{22} kg (mass of Moon)

$$r = r_1 + r_2$$

$$r_2 = r - r_1$$

$$m_1 * r_1 = m_2 * r_2$$

$$m_1 * r_1 = m_2 * (r - r_1)$$

Summarize the results in a plenary session.

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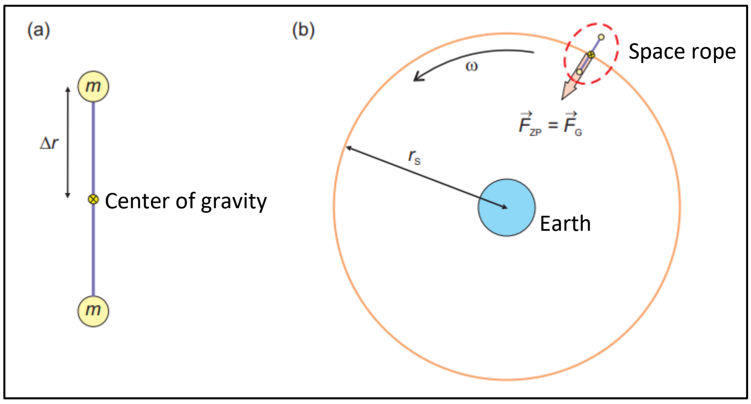
3. Space ropes and tidal locking

- What is a space rope and what are space ropes used for?
  - Two point-like capsules of mass m are connected by a massless, rigid rope. The center of gravity of the arrangement lies in the middle of the rope, at a distance Δr from both capsules. The length of the rope is therefore 2Δr (see figure).
  - The relationship between the orbital velocity and the radius of the circular path can be obtained from the condition "centripetal force= gravitational force." This results in Kepler's third law
  - The space rope travels around the Earth at a constant angular velocity. When the upper capsule is further away from Earth than the center of gravity, the gravitational force is weaker here. It is lower than the centripetal force required for movement at the angular velocity ω. The rope prevents the capsules from drifting apart; if it was elastic, it would stretch due to the rope force.



  - The rope force is directed inward. It prevents the upper capsule from increasing its distance from the center of gravity. If the rope is cut, the two capsules drift apart. **The rope has the task of preventing this drifting apart.**
  - If the rope is not rigid but slightly elastic, it stretches under the influence of these forces. The same happens with the rock. Due to the effect of the tidal forces, it causes tension to build up in the rock. It deforms elastically, and the surface rises. Over time, the rock deforms and begins to "flow."

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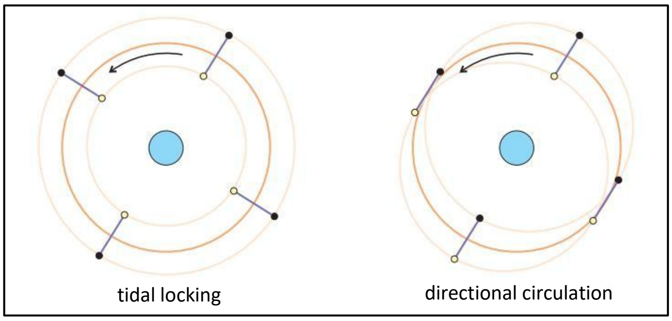
3.1. **Imagine that you are a passenger in such a capsule and are holding an object in your hand. Think about what would happen if you let go of the object. Name the function you are performing when you hold the object and apply the situation to the example just performed.**

3.2. **Gezeitenkräfte und gebundene Rotation: Analysiere, was die Zentripetalkraft damit zu tun hat und was den Mond auf seiner Bahn hält. → E.g. Hammer thrower – Work in pairs to discuss**

- The space rope mentioned runs in tidal locking around the Earth, just like the Moon
- The outer capsule (black) orbits the Earth at a greater distance than the center of gravity
  - ➢ therefore, a greater centripetal force must act on it, which contributes to the tension of the rope. Tidal locking is a stable form of motion for the space rope



- Tidal locking = Directional rotation+ Rotation around its own center of gravity. In tidal locking, the rope has changed its orientation in space by 180° after half a rotation (the black capsule is now at the bottom left). After a full rotation, it has rotated once around its center of gravity.

➢ Only 2/3 of the rope force is due to tidal forces. The remaining third is caused by the centripetal force associated with the rotation of the rope around its center of gravity. This also tensions the rope. However, this component is not a tidal force as defined. In other words, **the artificial gravity in the capsules is not caused solely by tidal forces, but also by the centripetal force of the rotational movement.**

Compile the results in a plenary session.

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3.3. Task:

Artificial gravity is generated in the manner described above in a 50 km long rope running around the Earth at an altitude of 400 km (corresponding to the altitude of the ISS). Using the rope force in the end capsules, calculate the "gravitational acceleration" in the capsules compared to the acceleration due to gravity *g*.

$$F_{rope} = 3\,G\,m\,m_E * \frac{\triangle r * 10^3}{(r_s * 10^3)^3}$$

$$\alpha_{tide} = \frac{F_{Seil}}{m} = 3\,G\,m_E * \frac{\triangle r}{r_S^3}$$

$$G\ (gravitational\ constant) = 6,67 * 10^{-11} \frac{m^3}{kg * s^2}$$

$$r_{Earth} = 6370\ km$$

$$\triangle r = \frac{1}{2}\ rope\ length$$

$$m_E = 5,97 * 10^{24} kg$$

Compile the results in a plenary session.

3.4. Take a close look at the following maps showing the global relief and global crustal thickness of the Moon and interpret how differences in height and crustal thickness could have arisen, especially when comparing the near side of the Moon with the far side of the Moon. You can also view the maps in 3D in the app.

In the early stages of the Moon's development, its distance from Earth was much smaller, and accordingly, Earth exerted much more energy on the Moon. This caused it to be completely surrounded by lava due to the heat. Under the influence of Earth, the Moon quickly entered into a bound rotation, which is still the case today.

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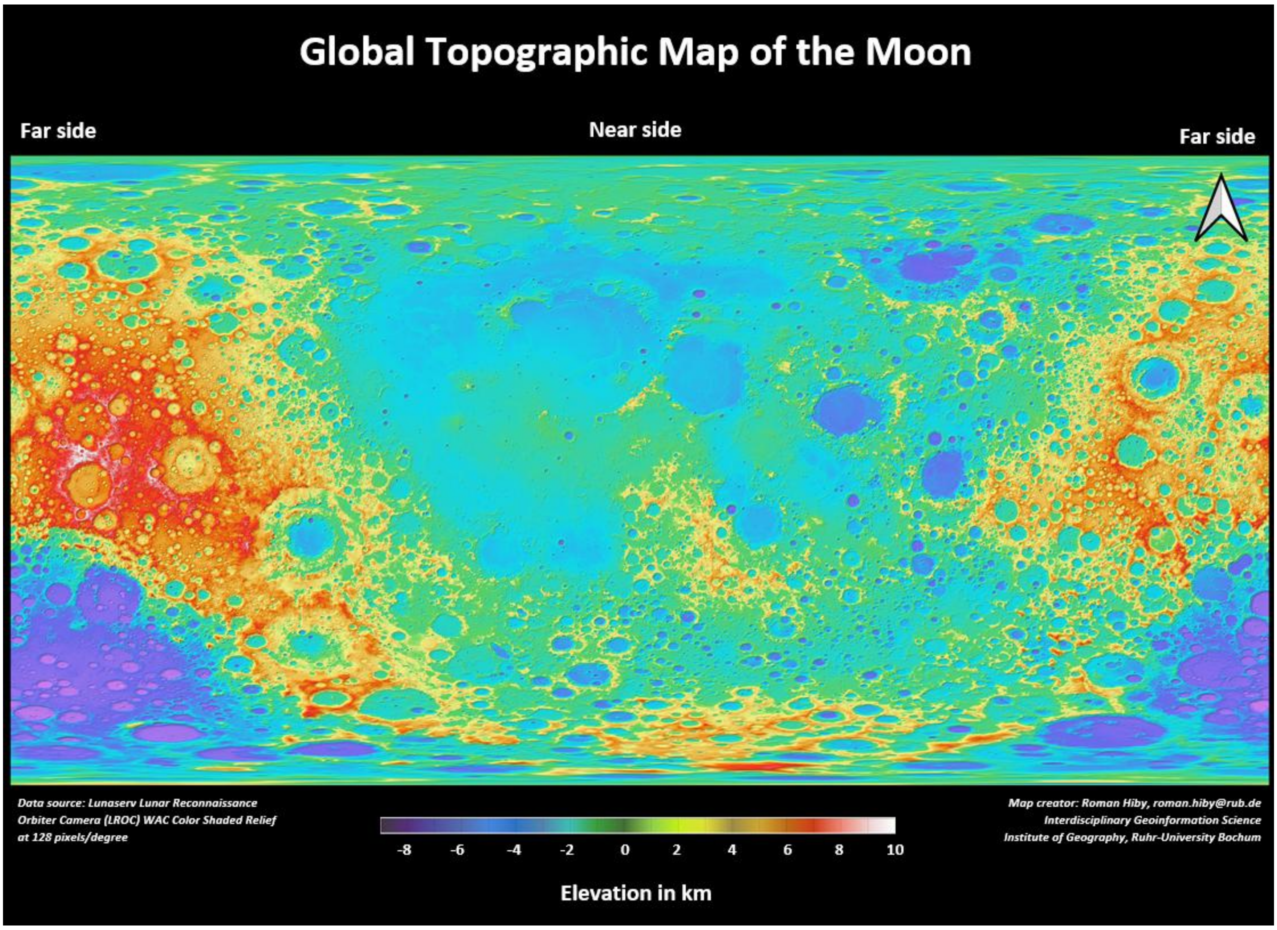

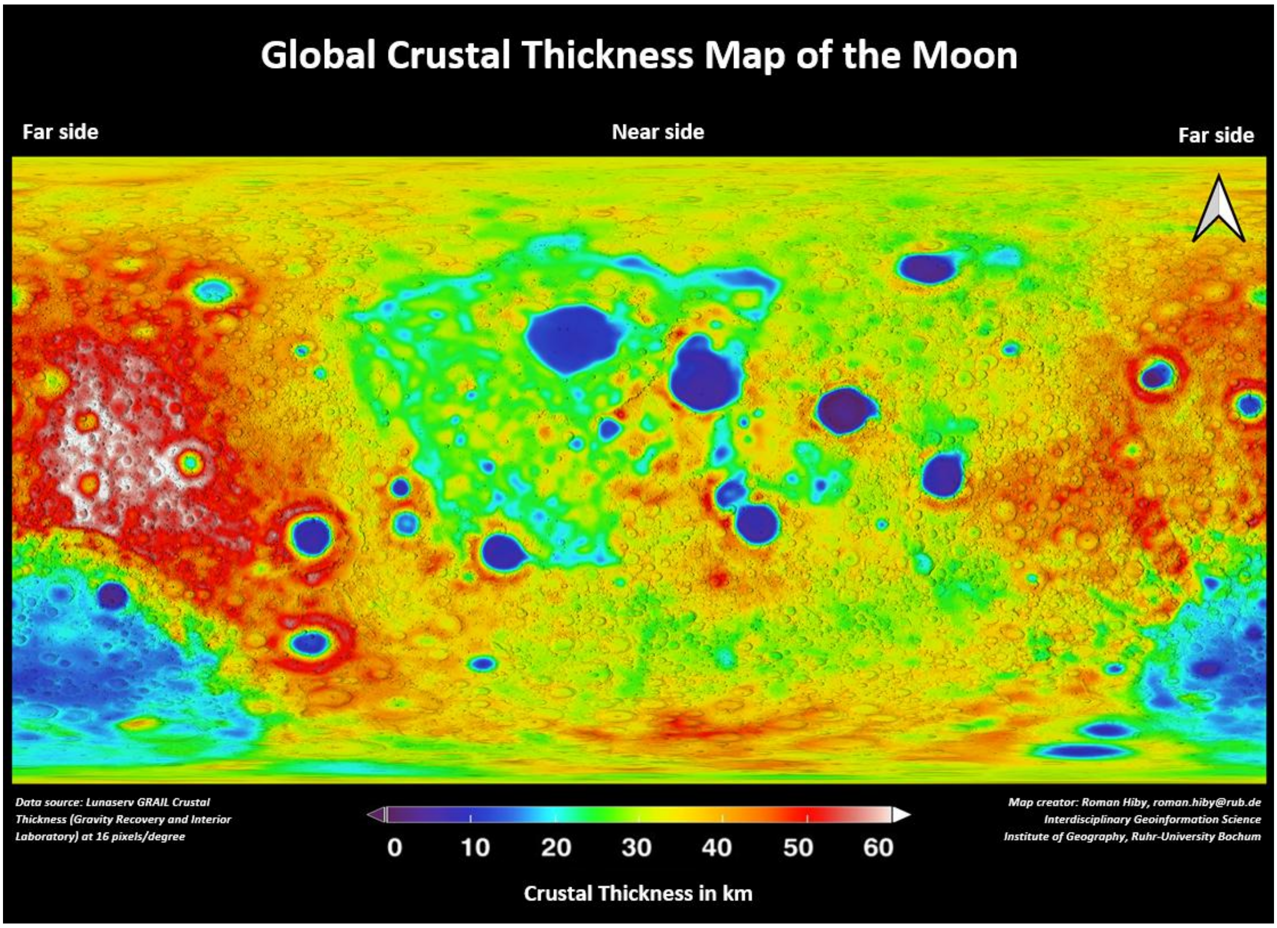

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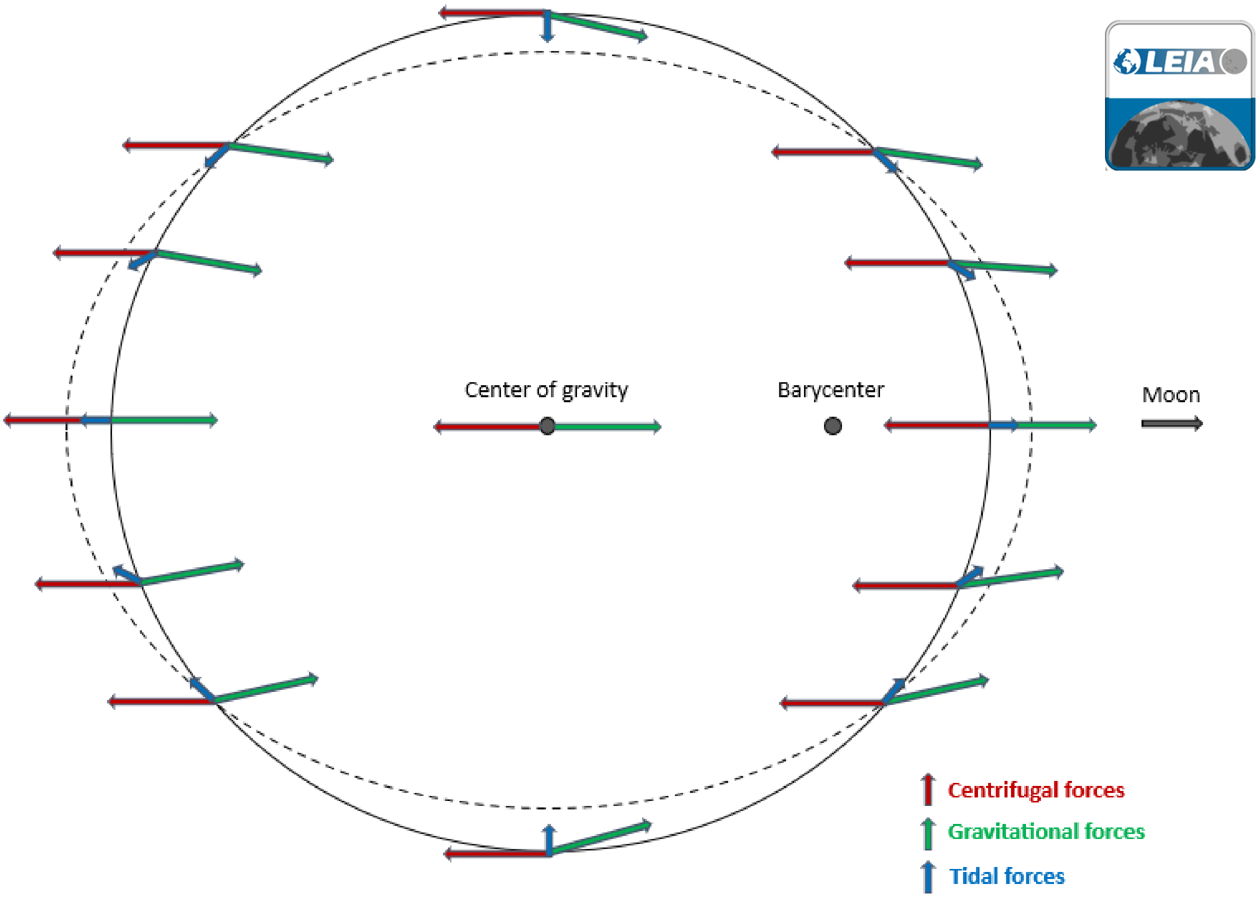
3.5. Explain why high tide or low tide occurs every 12:25 hours on average. Take a look at the Earth-Moon system in the app to learn more about the tides.



- The illustration shows the effects of tidal forces on the Earth. The Earth rotates around its own axis once a day. The side facing the Moon and the side facing away from the Moon experience high tide, while the respective 90° positions experience low tide. Floods occur equally on both sides of the Earth. This is due to the gravitational pull exerted by the Moon on the Earth. The gravitational force of the Moon is stronger on the side facing the Moon than on the side facing away from the Moon due to the different distances to the Moon. Assuming that the Earth is a rigid or solid body, the gravitational acceleration is the same at all points on the Earth. It is exactly the same as the vector at the center of gravity (center of the Earth).

Compile the results in a plenary session.

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3.6. Analyze whether tidal forces also act on the Moon and to what extent they manifest themselves.

3.7. Roche stability limit:

Imagine that the Moon is moving towards Earth and determine how close the Moon would have to get to Earth to be torn apart by tidal forces. Use the Earth-Moon system in the app to help you.

- The strength of the tidal force depends on the distance between the bodies or objects involved
- When a celestial body approaches another with greater mass, the tidal force increases rapidly due to its dependence on the cube of the distance and therefore attempts to tear the lighter celestial body apart.
- The calculation is performed for rigid celestial bodies on the one hand and for liquid celestial bodies on the other.
  - ➢ The true Roche limit usually lies between these values, but is difficult to determine because other factors such as deformability and exact density distribution must be taken into account.

$$d = Roche\ limit$$

$$\rho_M = Density\ of\ main\ body\ (Earth) = 5,514\ g/cm^3$$
$$\rho_m = Density\ of\ secondary\ body\ (Moon) = 3,344\ g/cm^3$$

$$R = Radius\ of\ the\ Earth = 6.370\ km$$

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The following applies to rigid bodies:

$$d = R * \sqrt[3]{\frac{2\rho_M}{\rho_m}}$$

The following applies to fluid bodies:

$$d = 2,423 * R * \sqrt[3]{\frac{\rho_M}{\rho_m}}$$

3.8. Analyze the role of the Moon and the Sun in the formation of tides and explain the difference between them. Use the app to find out more about the individual celestial bodies and their relationship to each other.

3.9. Explain when we talk about spring tides and neap tides (high and low tides). You can also find information about it in the app at the Earth-Moon system.

4. Now summarize the formation of tides for a partner. Afterwards, write a letter to Johanna explaining the tides.

Then share your findings with the whole class.

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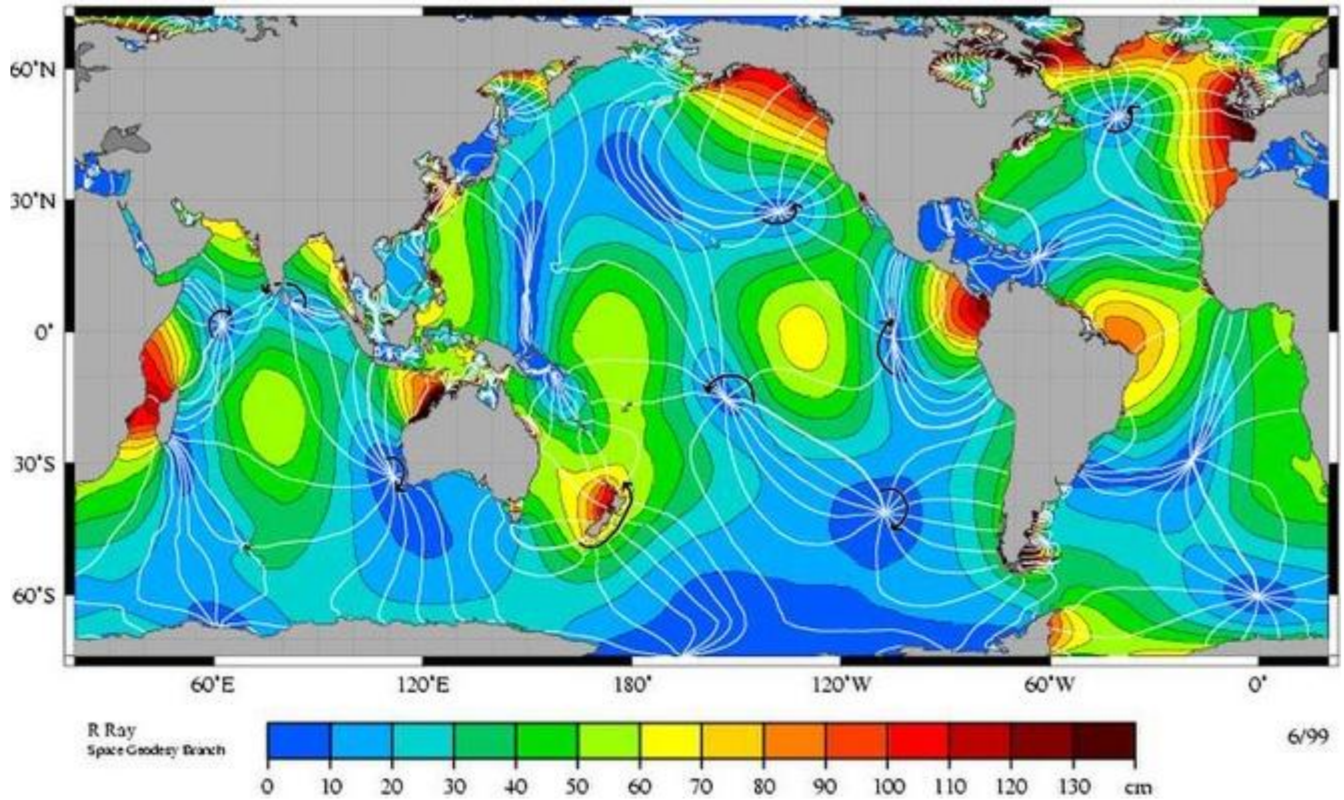
5. **Additional task: Explain which geographical factors influence the strength of tides on the Earth and why they are stronger in certain places. Use the following map to help you.**



6. **Additional task: Think about what life on Earth would be like without the Moon and whether we could even live without it.**

Because the Moon's orbit is already synchronized, the tidal forces acting on the Moon cause it to move further and further away from Earth by about 4 cm per year due to its orbital angular momentum. Since the total angular momentum of the Earth-Moon system is a conserved quantity, the decrease in the Earth's rotational angular momentum is balanced by the increase in the Moon's orbital angular momentum. The Moon and Earth thus stabilize each other in their system.

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