



TRACK YOUR ATMOSPHERE

Intellectual Output IO3 GNSS and Atmosphere Workshop

GNSS = Global Navigation Satellite Systems

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1 Introduction

The global navigation satellite systems (GNSS) allow for the calculation of the atmospheric water vapor content. This is very useful for short-term weather prediction as well as for long-term climate models. This reader is an attractive, interdisciplinary course where students learn about the related physical background. At the end, they will be able to calculate the amount of precipitable water vapor by help of GNSS data.

1.1 Importance of Water in the Atmosphere

Water appears in the atmosphere as gaseous water vapor or in condensed form as clouds or even rain. Therefore, it has a large impact on the current weather and weather phenomena. However, as most dominant greenhouse gas, the atmospheric water vapor is also important for long-term climate research and prediction.



Fig. 1-1 Water vapor is important for weather forecast.

1.2 Structure and Composition of the Atmosphere

The atmosphere appears to be only a very thin layer around the earth. In numbers the radius of the earth is about 6400 km, while the atmosphere reaches a height up to 1000 km - thus the atmosphere height is only about one sixth of the world radius!

Additionally, the air containing part of the atmosphere reaches only a height up to approximately 30 km. Up to this height 99% of all material-mass is found. This means 99% of all gases and condensed substances. If we reduce the distance to the earth about one half, 15 km, there is still 90% of all mass found.

This bottom layer of the atmosphere is called the

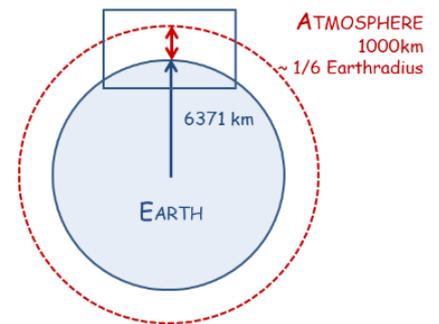


Fig. 1-2 Cross section of earth and atmosphere

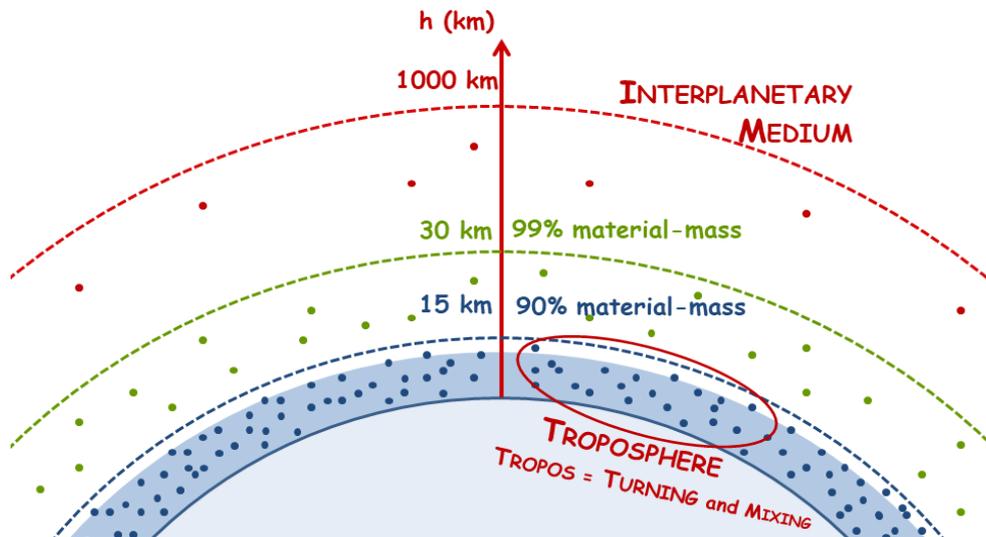


Fig. 1-3 Material distribution in the earth atmosphere.

"troposphere". Since many important events are proceeding here, it was named after the Greek word "tropos" which means "turning" or "mixing". This mixing becomes obvious when observing the way of a water molecule from the surface through the atmosphere.

Its journey starts in the deep wide ocean. When it is close to the surface, it might eventually evaporate and rise as water vapor into the sky. If appropriate conditions are given, our water molecule will become liquid again and form with millions of other molecules a cloud. From there, it can fall back as rain to the earth surface, thus finishing its journey through the atmosphere. Such a process needs about seven to ten days. And indeed, 85% of all water vapor in the atmosphere originates from the ocean, while the remaining 15% were evaporated from the land.

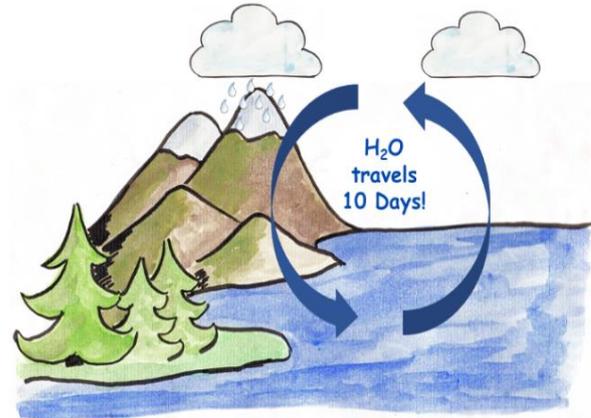


Fig. 1-4 Water circuits between oceans and atmosphere.

1.3 Determination of the Water Vapor Content in the Atmosphere

If we remember the vertical structure of the troposphere, we found out that about 90% of all mass is located in the upper 15 km. However, the main part of the water vapor is found in the first 5 km above the surface. This was found out by radiosounding, a method which uses sensor equipped balloons that flew vertically through the troposphere and deliver data like the water content at each desired height above the surface.

Nowadays, or more precisely since the early nineties, there exists a new method in addition to radio sounding, which uses the global navigation satellite systems (GNSS). These systems are commonly used for the determination of a position on the earth. One of these systems is a very famous one, the global positioning system (GPS) of the USA. However, there are also other systems like the Russian GLONASS or the European Galileo. All of these systems are based on satellites that surround the earth in a height of roughly 20.000 km and send permanently signals to the earth. Such a signal travels with the speed of light and reaches the surface in approx. 70 ms, which is actually seven hundredth of a second. But on its way, it has to pass the dense layer of the atmosphere molecules. These molecules are the constant occupants like Nitrogen and Oxygen, with an appearance of 78%

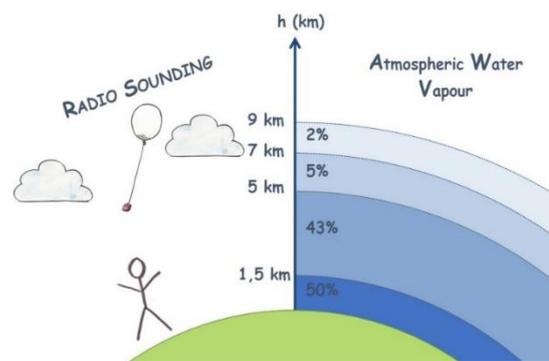


Fig. 1-5 Radio sounding provides information about the atmospheric water vapor content.

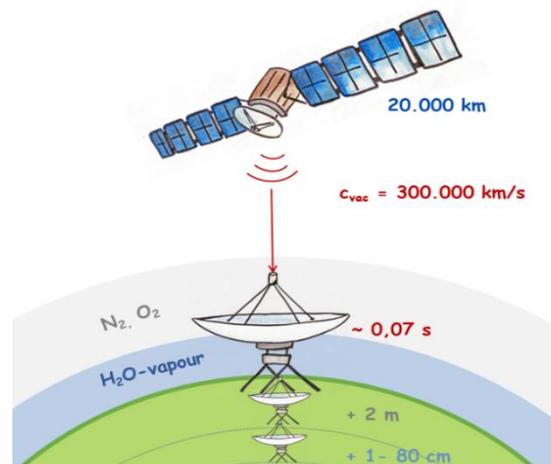


Fig. 1-6 Components of the atmosphere reduce the speed of the satellite-signal, as if the receiver were placed below the earth surface.

and 21% respectively and the varying amount of water vapor. The constant -"dry"- part, Nitrogen and Oxygen, produces the signals travelling delay of about 1 - 2 ns. When converted this time delay into a distance, it seems as if the signal travels 2 m further into the earth. This calculation is fairly exact and varies only about 1% within a few hours.

As it happens, the actual measured distance varies much more. This is the so called "optical path length" (see Sect. 4.2.4). The reason therefore is the strongly varying water vapor content of the atmosphere, which slows down the signal as well. Simply said, a low water vapor content adds a small distance while a high content adds a large distance to the satellite receiver systems. This additional distance varies from 1 - 80 cm.

Thus, we can calculate the water vapor content in the atmosphere by measuring the "extra" distance between satellite and receiver.

1.4 Topics Addressed in this Workshop

The aim of the project is to evaluate weather phenomena by calculating the atmospheric water vapor by measuring the distance of a satellite signal from the earth orbit to the earth surface. The satellites are provided by GNSS such as GPS, GLONASS or Galileo. Thus, we will develop basic knowledge of **satellites techniques** such as orbit calculation. The signal itself travels as wave, therefore we will learn about the behaviour of **mechanical and electromagnetic waves**.

The data derived from this procedure will assist weather forecast and climate prediction as well as the retrospective weather evaluation. Consequently, we will give a brief overview about physics happening in the **atmosphere** as well.

1.5 Questions

1. Why is it useful to measure the atmospheric water vapor?
2. How large is the earth radius compared to the height of the atmospheric shell?
3. In which part of the atmosphere is 90% of all mass found?
4. What does "tropos" mean?
5. How long does a water molecule need for its way from the ocean through the air back to the surface in average?
6. Name two methods for measuring the atmospheric water vapor content.
7. GNSS is the abbreviation for.....?
8. How fast does a GNSS-signal travel?
9. How can one measure the atmospheric water vapor content by GPS?
10. Think about topics, which are connected to GNSS-meteorology.

2 Mechanical Vibrations and Sound

2.1 Mechanical Vibrations

Mechanical Oscillation: Examples

- Swing on the playground
- Pendulum (clock)
- Sound
- Shaking house after door-slamming

An oscillation is a periodic movement, meaning a "back and forth" movement which is repeated in regular time periods.

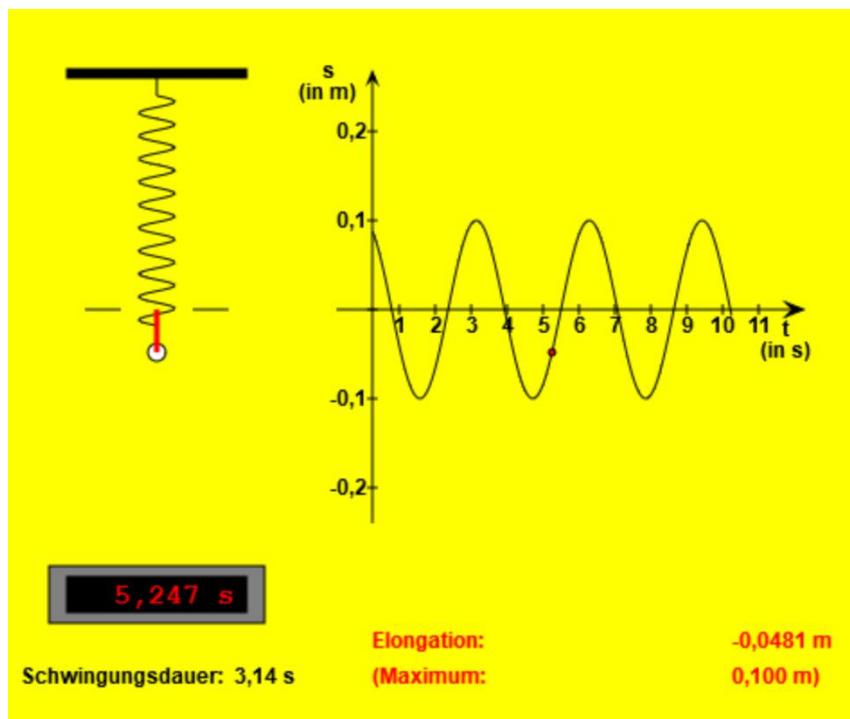


Fig. 2-1 Spring pendulum of Walter Fendt, https://www.walter-fendt.de/html5/phen/springpendulum_en.htm, CC BY-NC-SA 3.0 DE

Each oscillation has at each time a special **elongation** (distance difference to rest position). The maximum elongation is called **amplitude A**. The time period needed for a whole oscillation is called **period T**. The reciprocal of a period is called **frequency $f = \frac{1}{T}$** with the unit 1 Hertz = 1 Hz = 1 s⁻¹ = 1 oscillation per second.

For a harmonic oscillation, the path-time graph is sinus-shaped.

2.1.1 Tasks

- Choose one of the following experiments and describe the setup as well as the applied parameters.
- Determine as exact as possible the period and frequency of the oscillation.
- Repeat the previous task with altered parameters.
- Revise your result, if possible, with a given equation.

For some experiments you will need your smartphone and a physics-app: We recommend the following App: **PhyPhox** <https://phyphox.org> (it is available for Android and iOS in many languages)

- Measurement of a spring pendulums period (using the stop watch).
- Measurement of the period of a one side clamped leaf spring (using the stopwatch).
- Measurement of a spring pendulums period and elongation (using PhyPhox, acceleration without g).
- Measurement of a tuning forks period (using PhyPhox).

Chose "Audio Scope", strike the tuning fork and hold it on the display of your smartphone.

- Measurement of a wooden block's wagging vibration (using PhyPhox Audio Scope).
- Measurement of a tuning fork's frequency (equipped with an additional mass)
- Measurement of a partially filled wine goblet's frequency.

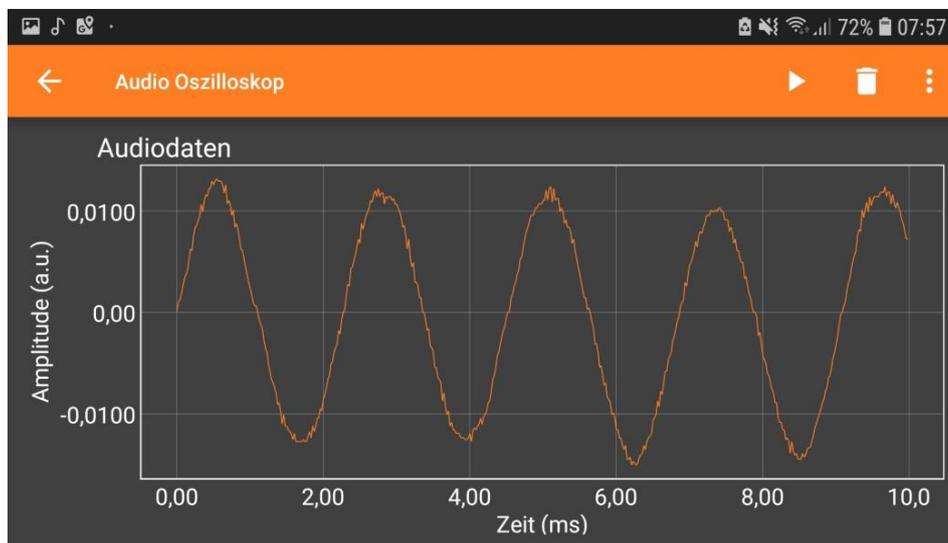


Fig. 2-2 Audio Oscilloscope (x-axis time in ms, y-axis amplitude in a.u.)

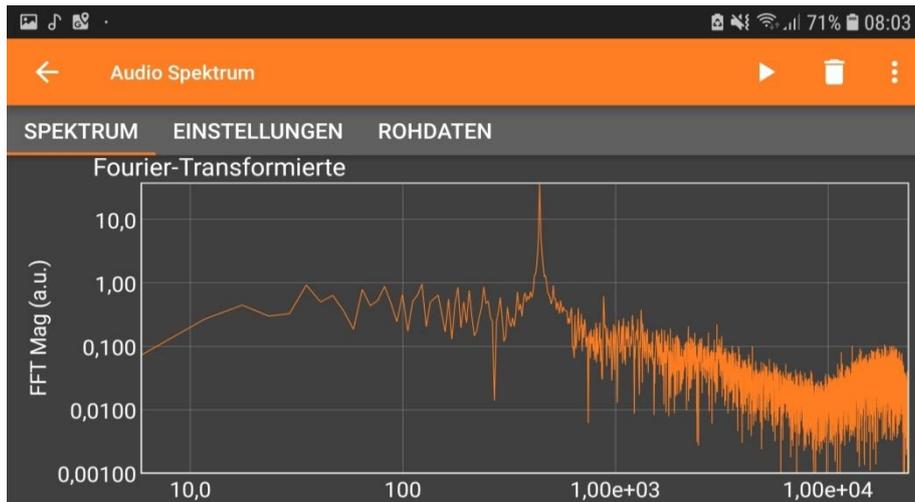


Fig. 2-3 Audio Spectrum,
(x-axis: frequency in 1/s, y-axis Fourier Transform Magnitude)

2.2 Mobile Phone as a Spring Pendulum

2.2.1 Experiment

A spring pendulum is equipped with a mobile phone of the mass $m = 128,3 \text{ g}$. The oscillation is recorded by the mobile's accelerometer. Tasks:

- Sketch the experimental setup.
- Use the $a(t)$ -plot to determine the period T as precisely as possible.
- Calculate the frequency f .
- Calculate the angular frequency as well, thus providing the true oscillation amplitude

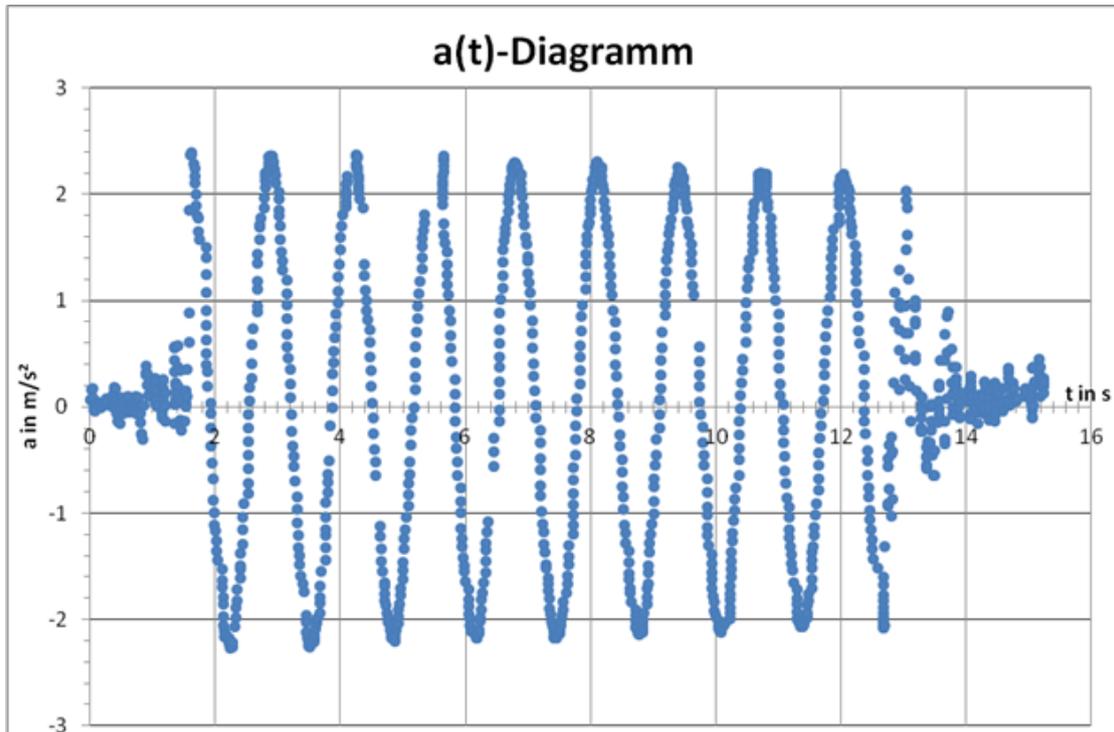
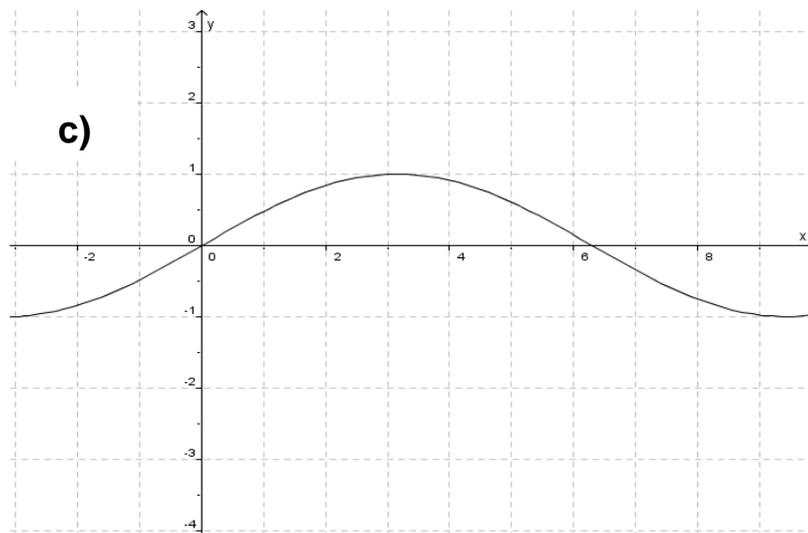
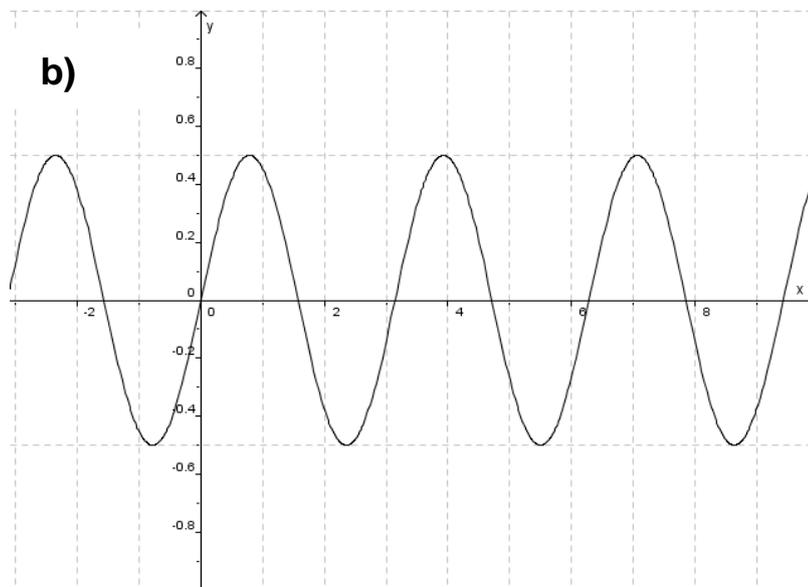
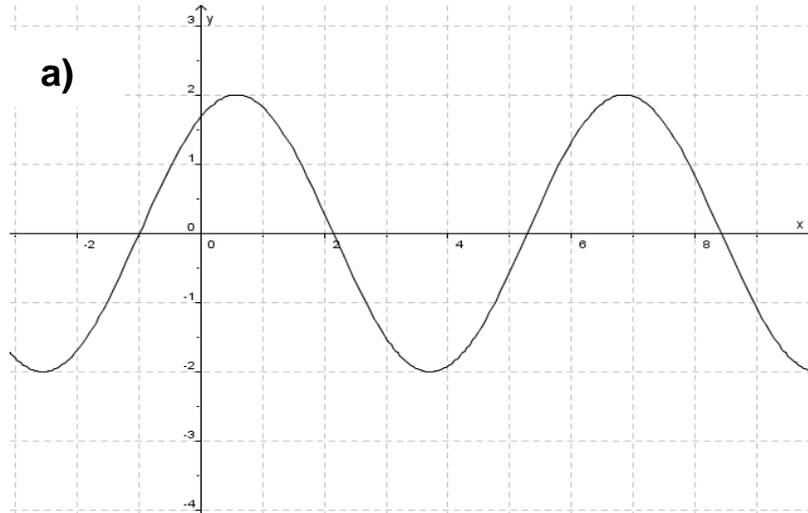


Fig. 2-4 acceleration plot (x-axis time in s)

2.2.2 Task

Three graphs of sinus-shaped functions are given. Determine each functions equation!

Basic form: $y(x) = y_0 \sin(\omega x + \varphi)$



3 Mechanical Waves

3.1 Wave Propagation

Examples of mechanical waves

- Wave on an elastic rope, spring
- Water Wave
- Sound Wave
- Earthquake Wave

In a coupled oscillatory system ("medium"), one oscillator after another performs the movement dictated by the origin of motion.

The further away an oscillator is from the first, the later it will be caught by that movement. This propagation does not transport matter but energy.

The propagation speed is usually named c .

E.g. $c_{Air} = 330 \text{ m}\cdot\text{s}^{-1}$ is the speed of sound in air.

The **propagation direction** of the wave (see P in the illustration) is the direction in which the wave travels

E.g. Water waves propagate in all directions from the point of disturbance.

The **oscillation direction** of the wave (see A in the illustration) is the direction in which the oscillatory parts/particles of the medium vibrate

E.g. the water surface of a water wave swings up and down.

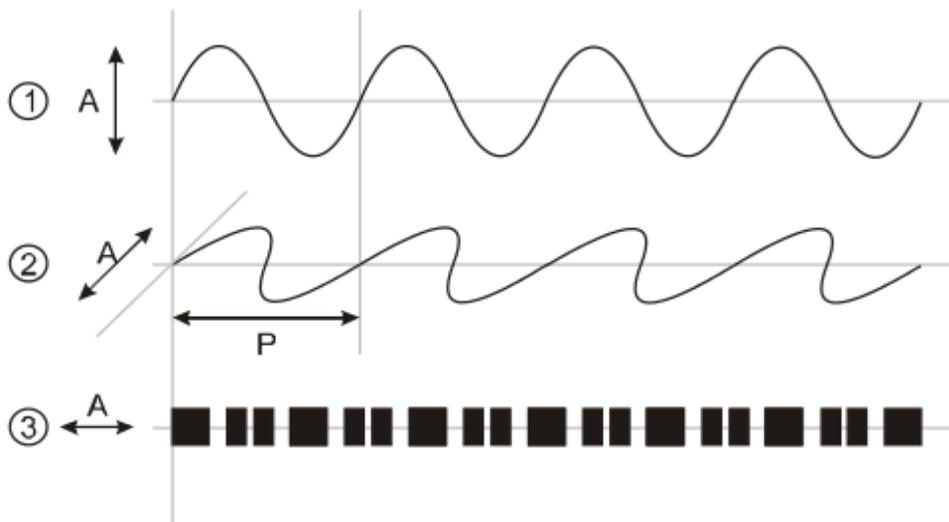


Fig. 3-1 Types of mechanical waves

(CC BY-SA 3.0, <https://commons.wikimedia.org/wiki/File:Wellen.svg> by Stefan-Xp)

We distinguish:

- **Transverse waves:**
The oscillation direction *A* and the propagation direction *P* are perpendicular, as in case (1) and (2) of the figure. If the oscillation direction *A* of a wave only points in one direction, then the wave is polarized.
- **Longitudinal waves:**
Vibration direction *A* and propagation direction *P* are parallel, in the same direction as in case (3) of figure 3-1. Polarization therefore does not occur with longitudinal waves.
- **Harmonic waves:** Sinusoidal waves
- **Damped waves:** Decrease in amplitude during propagation
- **Standing (or stationary) waves:** When they overlap fixed *nodes* (N) and *antinodes* (A) occur (Fig. 3-2).

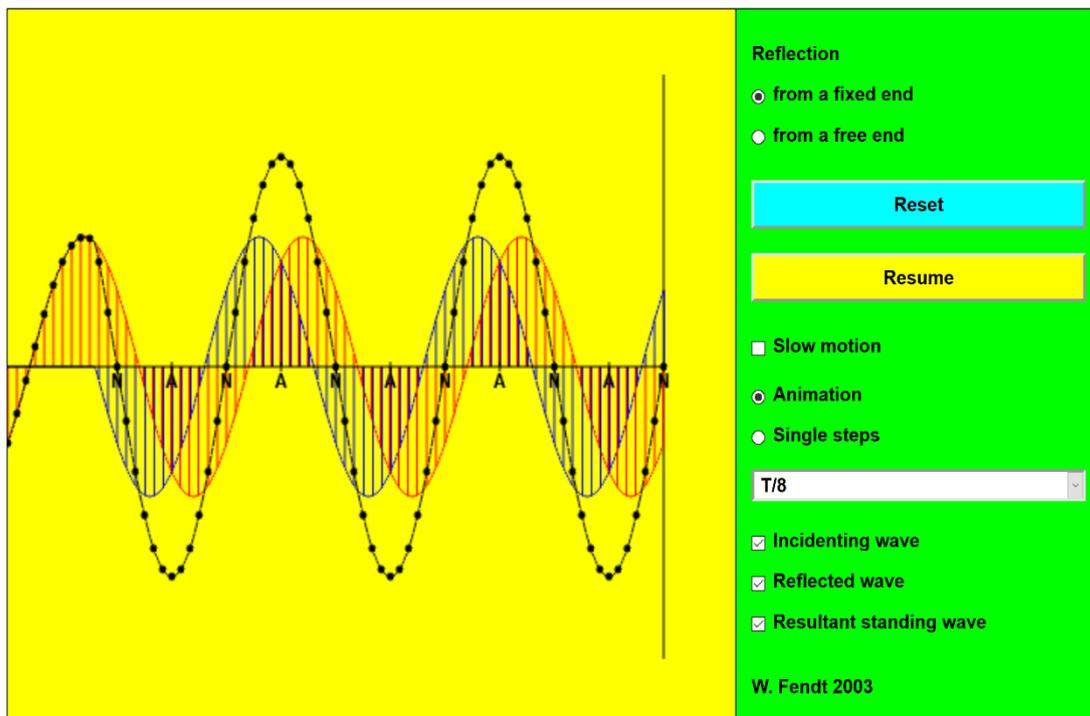


Fig. 3-2 Applet by Walter Fendt
(CC BY NC SA 4.0, https://www.walter-fendt.de/html5/phen/standingwavereflection_en.htm)

For the **description of mechanical waves**, the most important parameter is the **propagation velocity *c*** (in m / s). This is the speed at which a wave crest or wave trough moves in space, or more generally speaking, the speed at which the phase (displacement) moves in space.

To describe **harmonic waves** use the following:

Frequency *f* (in Hz = 1/s) (or oscillation period *T*)

With which the particles of the medium vibrate (Reminder: $f = 1/T$)

Wave length λ („lambda“ in m)

Spatial distance between two wave crests or two troughs

For harmonic waves the fundamental relation applies: $c = \lambda \cdot f$

„propagation speed = wavelength multiplied by frequency “

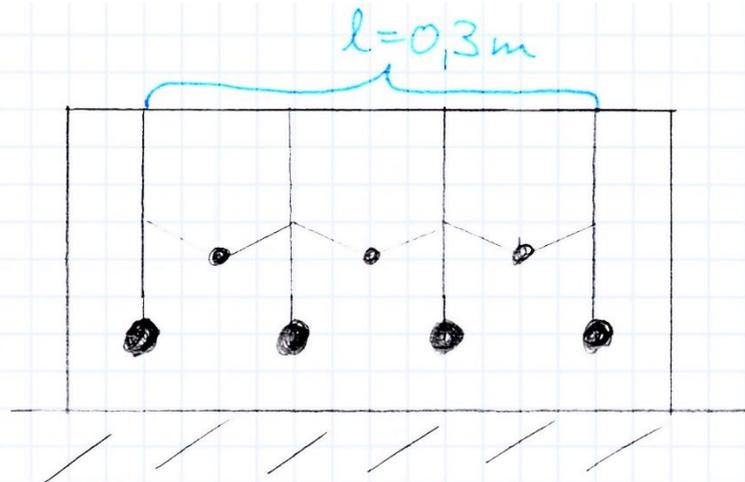
3.2 Experiments

- Choose a model experiment and describe it in detail (also with a sketch). Measure the length of the medium.
- Determine the propagation velocity c by measuring the time it takes for the waves to traverse the medium several times.
- Make a guess on what c depends on. Change a parameter accordingly and repeat the determination of c .
- Present the experiment to your classmates.

Model experiments

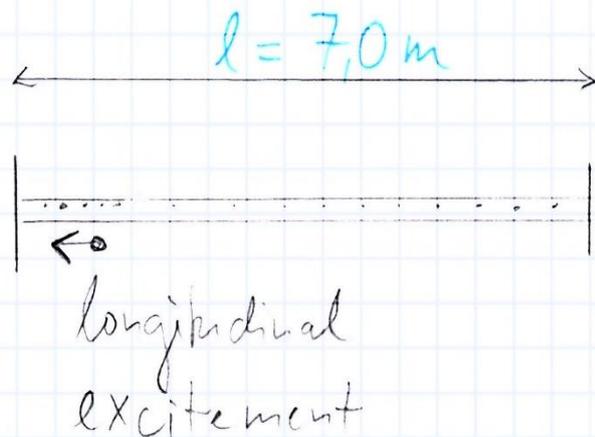
- Several coupled pendula. Measure the time the longitudinal/transversal wave travels back and forth.

Four coupled thread pendula

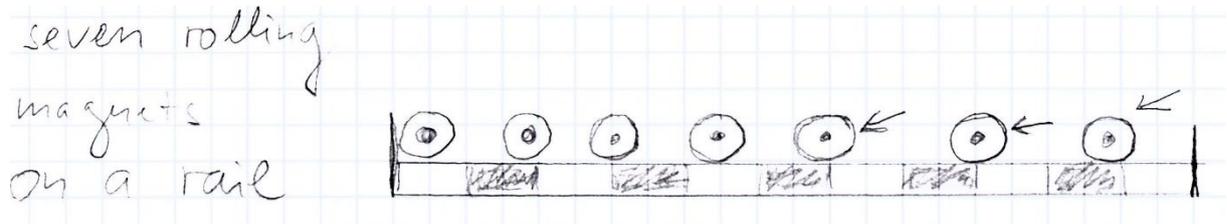


- Rubber band. Measure the time for 10 reflection, this means $s = 20 l$.

propagation of waves in a stretched-out rubber band



3. Rolling magnets on a rail.



4. Standing waves with a rubber band with motor and frequency generator.
5. Wave machine ("skeleton").
6. Standing waves in a current-carrying string.
7. Monochord: Dependence of frequency and speed of sound on the string tension.
8. Measurement of the propagation of a seismic wave in the gym (swinging floor) with the smartphone
9. Experiments with Slinky

Slinky is a long steel spring. You also need a long measuring tape (25 m) and a stopwatch (if necessary mobile phone) and you need some space - preferably the school corridor.

Place the slinky flat on a smooth surface (e.g., linoleum floor). Working in pairs, everyone holds an end. Make sure the slinky does not form a knot or does not stretch too much.



Generate successive harmonic, transverse and longitudinal waves. Can you (with your partner) create a standing wave?

Fig. 3-3 Slinky by Roger McLassus (CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=554020>)

- a) Now you let a "pulse" (longitudinal or transversal) travel through the slinky by giving one short push (longitudinally or sideways). What do you observe when the wave arrives at the other end?
- b) Carefully stretch the slinky to the length $\ell = 12.0$ m. Measure the time t , needed for a transverse excitement to move back and forth through the slinky. Repeat the time measurement. Calculate the propagation velocity $c = 2\ell / t$.
- c) Repeat part 3 with a larger and a smaller length ℓ .
- d) Repeat part 3 with a longitudinal impact.

Repeat the entire Slinky experiment with a long, stretched rubber band. Here you can feel how the pulse is running back and forth through the band several times

4 Refractive Index and Snell's Law

4.1 Determination of the Refractive Index

In these experiments we want to measure the refractive index of a transparent plastic body (acrylic glass cuboid) by two different approaches. For each approach, we use a red light laser.

4.1.1 Approach A: Determination of the refractive index by aid of a laser range finder (LRF)

Operation principle: https://en.wikipedia.org/wiki/Laser_rangefinder

Measure the dimensions of the acrylic glass cuboid (height, width, depth) by adjusting the LRF to it. Doing this, the laser beam should be positioned **outside** the cuboid during the first measurement (h, w, d) and **inside** during the second (h', w', d'). Calculate the quotient as indicated.

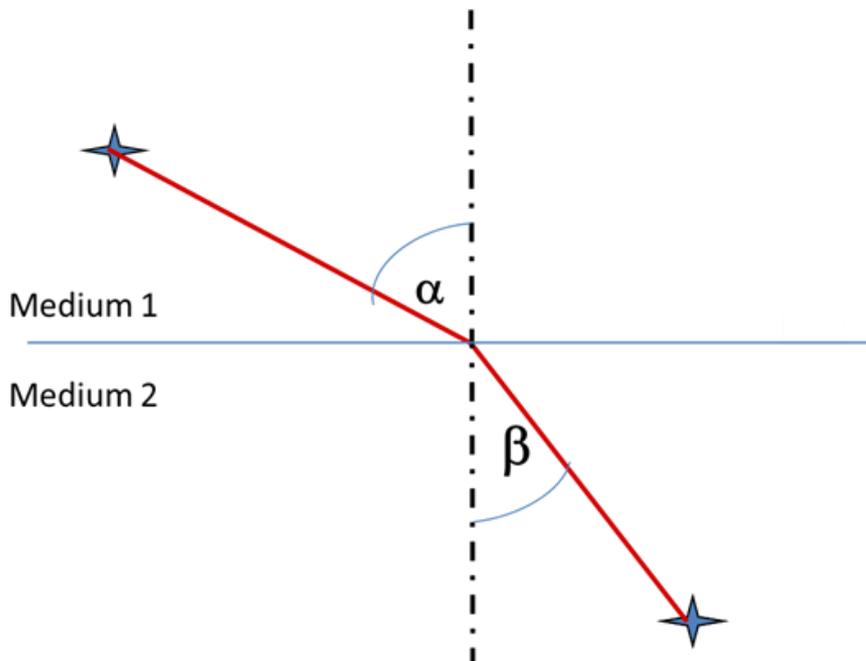
	x in mm	x' in mm	Quotient $n = x'/x$
Height			
Width			
Depth			
Average			

4.1.2 Approach B: Determination of the Refractive Index by aid of a Laser pointer

For this approach, we apply Snell's law of refraction, which describes the refraction of light passing the boundary between two media of different density.

$$\frac{n_2}{n_1} = \frac{\sin \alpha}{\sin \beta} \quad \text{Eq. 4-1}$$

Here, n_1 refers to the less dense medium 1 (air) and n_2 to the denser material 2 (acrylic glass). The angles are measured in relationship with the normal, while α is the incident angle and β the refraction angle.



We use a RAY Box, which is laser pointer which creates beams of light that graze a surface. Additionally, you will need a white sheet of paper, a sharp pencil, a triangle ruler as well as colored pens.

Take care that you prepare your drawings as large and exact as possible!

1. Place the paper upright and draw in the middle a horizontal line. This line represents the boundary between medium 1 (air, top) and medium 2 (plexiglass, bottom).
2. Draw the normal (perpendicular dotted line) onto the boundary.
3. Draw in the lower half of the page (medium 2) a refracted ray with a refraction angle of $\beta = 35^\circ$. Adjust the plexiglass cuboid lining up precisely with the boundary.
4. Switch on the RAY Box and adjust the incident ray confirming with the already drawn one.
5. Mark the path and draw the incidence ray as well as the incident angle.
6. Repeat the steps 3. - 5 two times. Draw the related rays in different colors.
7. Measure the three pairs of angles and complete the table.

Nr.	α in $^\circ$	β in $^\circ$	$\sin \alpha / \sin \beta$
1			
2			
3			
Average:			

4.1.3 SWEET extra experiment

For this experiment, you need about a liter of **saturated sugar solution**. Put it in a recipient (small aquarium) so that it will be around 5 cm high. Then pour very slowly the same amount of water where you have stirred before just one drop of milk. The sugar water is much denser than the milky water, so that both liquids do not mix.

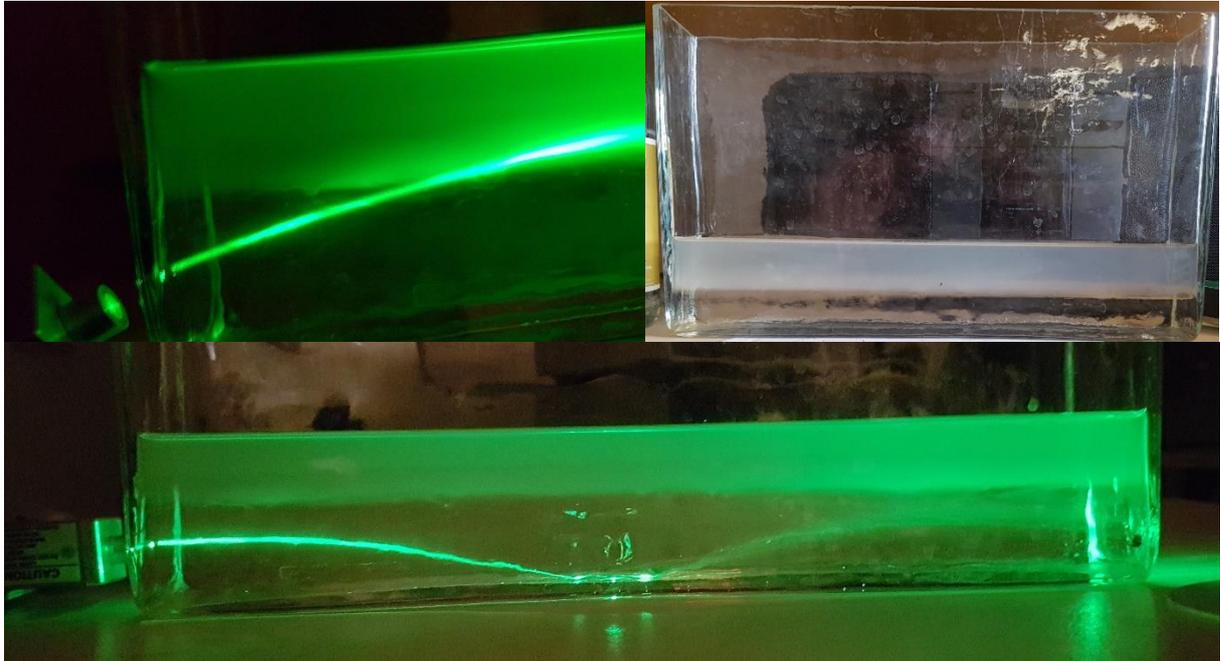


Fig. 4-1 Fotos by B. Reusch for TRYAT, [CC BY 4.0](#)

Now we show that both liquids also have different refractive indices. When you apply a laser beam passing from one liquid to the other the beam is refracted because the speed of light in the sugar water is lower than in normal water

When the laser beam enters the boundary of both solutions you can even see a bended beam and total reflection

This is also what can happen to any electromagnetic wave (e.g. light of a star, radio wave, microwave GNSS signal) travelling through the atmosphere. Its density is not constant so that the wave's propagation might be bended and undergo (total) reflection.

See e.g. <https://astrocampschool.org/refraction/>

4.2 Determination of the Refractive Index of Air

4.2.1 Principle

The refractive index of air is slightly higher than the index of vacuum ($n_0 = 1$). Its value varies with the pressure and the water vapor content of the air. For normal pressure (1013 hPa) and dry air, n_M is equal to 1.0002760. The determination of the small differences of the refractive indices between vacuum and air need specially designed interferometric experiments. The Michelson Interferometer is one possibility. This interferometer is based on an experiment performed by Michelson and Morley in the late 19th century.

The figure describes the principle of the measurements: a light beam is split into two parts, for example by a glass plate. Both beams are reflected by mirrors and interfere after a second reflection at the glass plate. On the screen typical interference pattern can be observed.

To determine the refractive indices of gases, a vacuum chamber is inserted in one branch of the interferometer. The chamber is then filled with gas at an adjustable pressure. The speed of light is influenced by the gas due to changes in the refractive index. As a result, changes of the interference pattern can be observed on the screen.

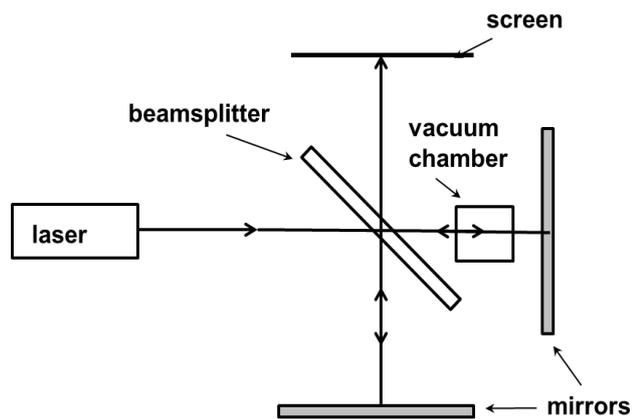


Fig. 4-2 Michelson Interferometer, Principle

The following section describes an experimental setup for teaching purposes and an example for the determination of the refractive index of air.

4.2.2 Experimental Setup

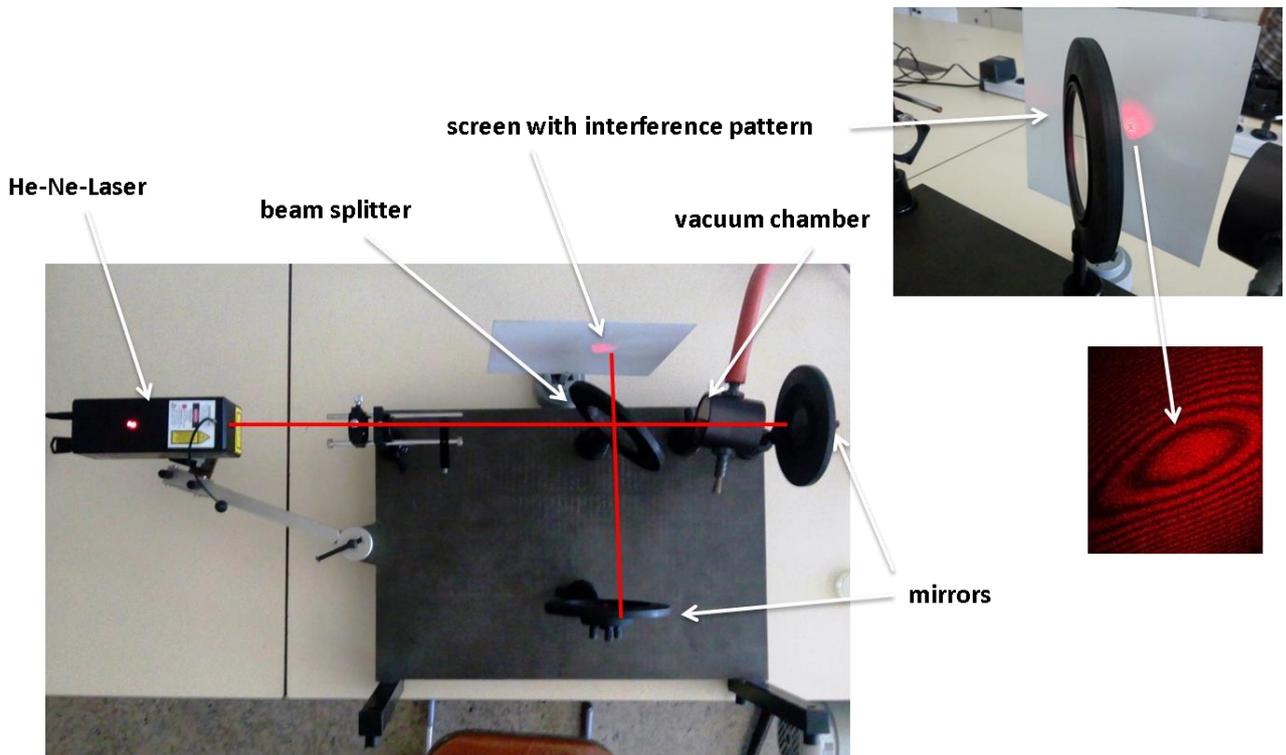


Fig. 4-3 Experimental Setup

(Components from Leybold Heräus)

- The light beam is emitted by an He-Ne-Laser and divided by a glass-plate mounted at an angle of 45°
- A vacuum chamber is inserted in one branch of the interferometer and evacuated ($p \approx 1 \text{ mbar}$).
- The inference pattern can be observed on a screen
- While the chamber is being vented with air, oscillating changes of the interference pattern are observable and will be counted. ($p_{\text{amb}} \approx 1013 \text{ mbar}$)
- Alternatively, the changes can be recorded with help of a light sensor (Fig. 4-4)

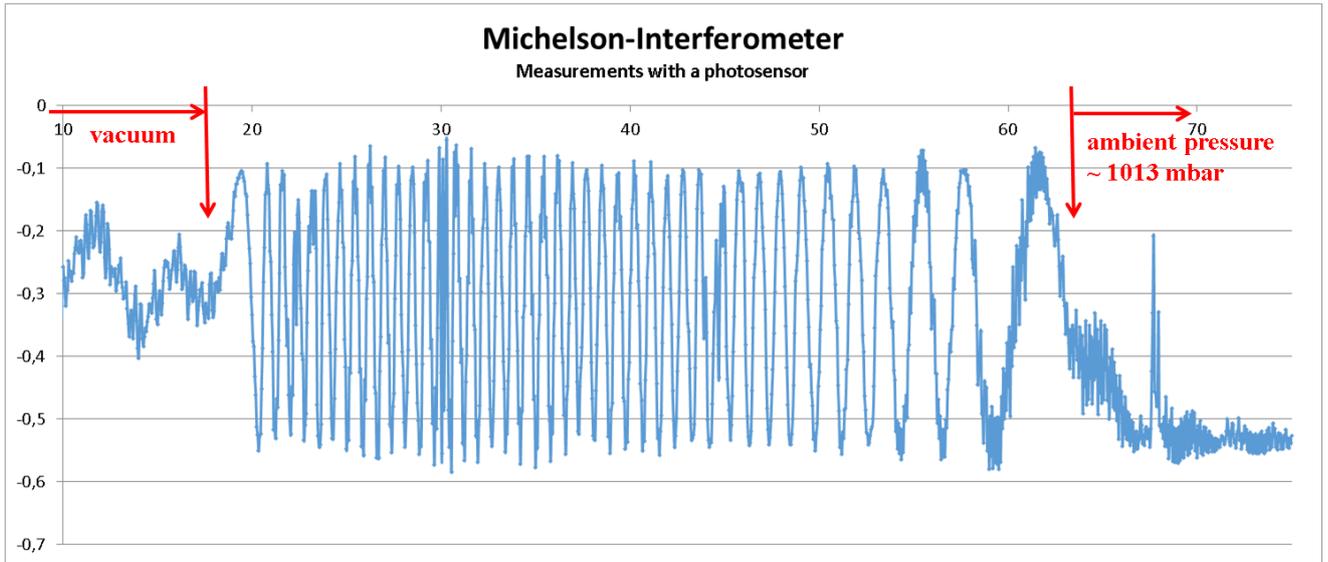


Fig. 4-4: Interference maxima and minima while venting the chamber (x - axis: time in seconds, y -axis: light intensity in arbitrary units)

4.2.3 Calculation of the refractive index

4.2.3.1 Theoretical background

In a medium such as air or water, the speed of light is reduced by a factor n relative to speed of light in a vacuum. n is called the index of refraction (or refractive index). It is always greater than 1, e.g. 1.333 for water, approx. 1.5 for glass, or 1.0003 for air as mentioned above.

$$c_M = c_o/n \tag{Eq. 4-2}$$

c_o, c_M : speed of light in vacuum and in the medium respectively.

A chamber of length d is crossed twice by the light. The "Optical Path Length" L inside the chamber follows:

vacuum: $L = 1 \cdot 2d$ $n_0 = 1.0000,$

with a medium: $L_M = n_M \cdot 2d$ $n_M > 1.$

Then the path difference between vacuum and a medium becomes:

$$\Delta L = n_M \cdot 2d - 2d = 2d(n_M - 1) \tag{Eq. 4-3}$$

The wavelength of the laser beam is medium-dependent as well. A higher index of refraction leads to a shorter wavelength. Therefore, varying the pressure in the chamber changes the number of wavelengths in one branch of the interferometer. As a result the interference pattern on the screen is changing. The change at the center of the interference pattern from one maximum through a minimum to the next maximum corresponds to one wavelength.

With this consideration, the path difference can be calculated: if a change of z maxima is observed, the path difference is equal to z multiples of the wavelength.

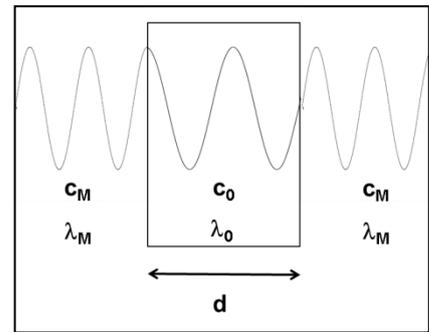


Fig. 4-5 Wavelength inside and outside a medium

$$\Delta L = z \cdot \lambda \tag{Eq. 4-4}$$

Therefore, with eq. 4-2 and 4-3:

$$z \cdot \lambda = 2d(n_M - 1) \text{ and } n_M = 1 + \frac{z\lambda}{2d} \tag{Eq. 4-5}$$

4.2.3.2 Result

In our experiment, we observed 42 maxima while venting the chamber with air from a pressure of 1 mbar to ambient pressure (see Fig. 4-4). The wavelength λ of the chosen laser was equal to 633 nm and the length of the chamber d was equal to 50 mm.

With these values, we calculate the index of refraction of air using eq. 4-5:

$$n_{\text{air}} = 1.00030 \pm 0,00002 \text{ , } (\Delta z = \pm 2, \text{ approx. } 5\%)$$

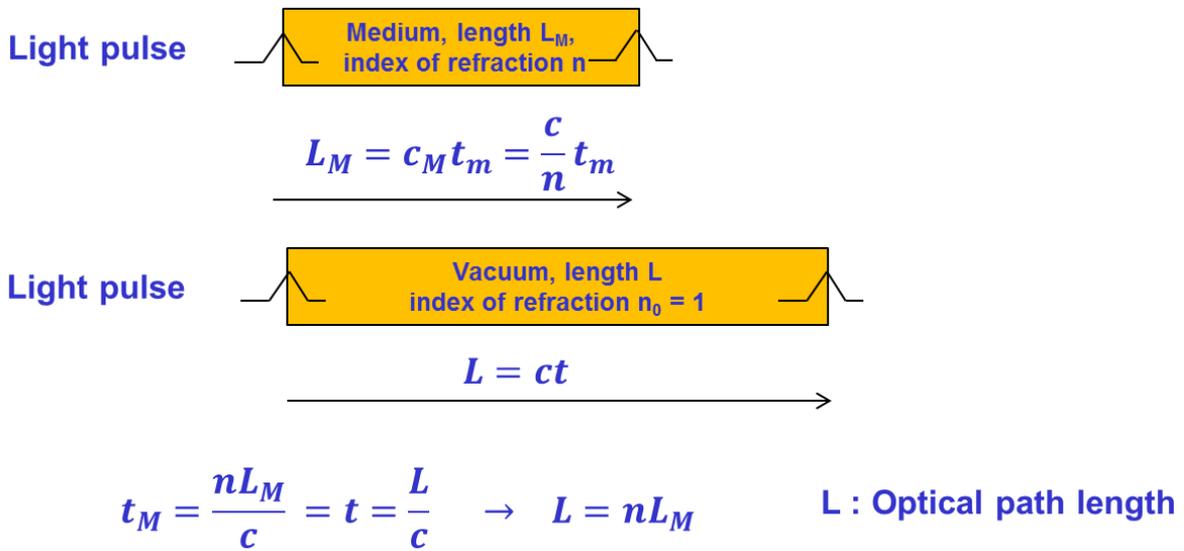
The value found in literature is: $n_{\text{air}} = 1.0002760$ (dry air, 1013 mbar)¹

The difference between dry and wet air is of the order of 10^{-6} . However, such a small difference cannot be measured with the chosen setup.

¹): Handbook of Chemistry and Physics 58th ed. p. E-224

4.2.3.3 Appendix: Optical path length

Wikipedia: In optics, optical path length ...is the product of the geometric length of the path light follows through the system, and the index of refraction of the medium through which it propagates.



5 Microwaves

5.1 Properties of microwaves

Microwaves are used in a wide range of applications: in the household for heating food, in radar speed measurement, in rain measurement, and in satellite transmission (mobile, WLAN, TV, GNSS, etc.). Microwaves are electromagnetic waves in the range of 0.3 m to 3 mm and a frequency range of 1 GHz to 100 GHz. They travel by line-of-sight at the speed of light.

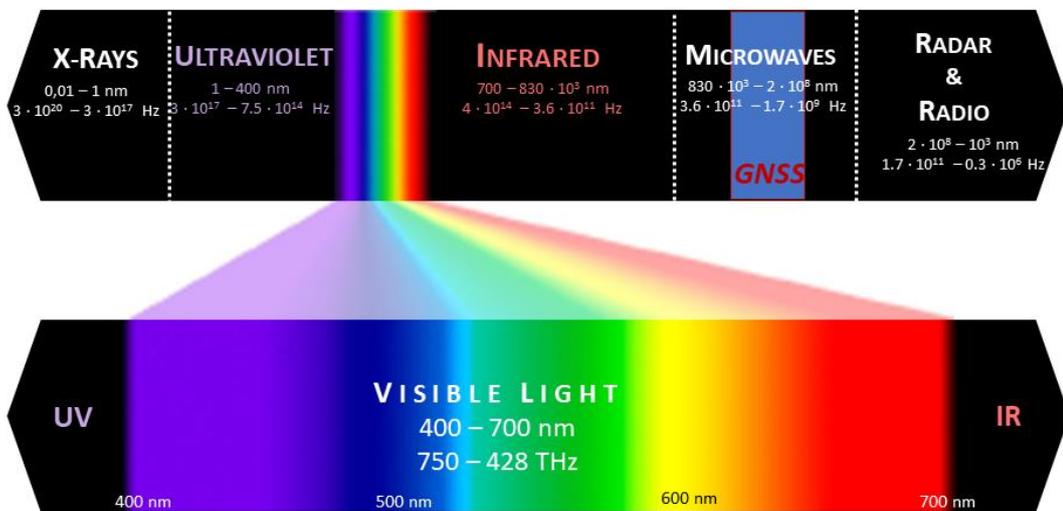


Fig. 5-1. Electromagnetic spectrum with indications of the wavelength, λ , and frequency, f , of the most representative radiations from shorter and most energetic, x-rays, to the longer and less energetic radiofrequencies. The blue box locates GNSS signal within the spectrum. An accurate description of the GNSS band is provided in figure 6-14; units: $1 \text{ nm} = 10^{-3} \mu\text{m} = 10^{-9} \text{ m}$, $1 \text{ THz} = 10^3 \text{ GHz} = 10^{12} \text{ Hz}$.

5.2 Experiments

With the illustrated antenna and the receiver the properties of microwaves have to be investigated. The experiments are carried out with a microwave frequency of 9.35 GHz, this frequency is significantly higher than the frequencies used for the GNSS positioning of 1.2 or 1.6 GHz. In particular, the absorption behaviour in water differs significantly.

Transmitting and receiving antennas consist of a dipole, the length of which corresponds to half the wavelength of the microwaves (Hertz dipole); from electro-technical point of view these are semiconductor diodes.

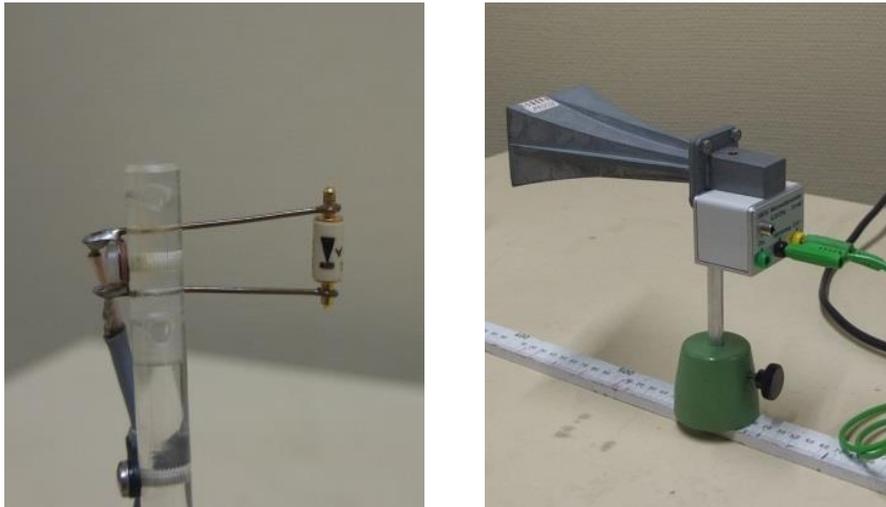


Fig. 5-2 a (left) Microwave antenna; b (right) microwave transmitter

Attention: Do not touch the contacts directly during the tests! The antennas are sensitive to electrostatic discharges!

Connect the transmitter to the power supply (12V AC) and the receiving antenna to a meter (measuring range mV). A precise voltage measurement is not necessary; the signal should be evaluated qualitatively.

5.2.1 Absorption

Place the receiving antenna at about 80 cm from the transmitter and examine the behavior of the microwaves when you hold the following materials into the beam path:

Material	mV
air	
plastic	
wood	
paper	
book / booklet	
damp paper	
glass	
hand	

5.2.2 Polarization

Turn the receiving or transmitting antenna 90° to a horizontal position.

Observation:

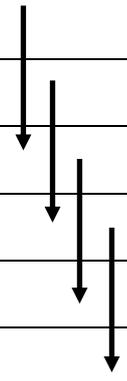
5.2.3 Reflection

Direct the transmitter antenna at an angle at the metal screen and use the receiving antenna to locate the point of maximum reception. Estimate if the law of reflection is met.

Result:

5.2.4 Measurement of the wavelength

Aim the transmitting antenna perpendicular to the metal screen at a distance of approx. 80 cm and position the receiving antenna approx. 6 cm in front of the metal screen, so that the received signal is at the minimum level. Mark this point with a tape measure or ruler as the zero point. Then slowly move the receiving antenna towards the transmitting antenna and record the distances of the minima and maxima from the zero point.

	d in cm		distance in cm
min	0		
max			
min			
max			
min			
max			
average value:			

Evaluation: In front of the metal screen "standing waves" with nodes and antinodes are formed, the distance between two nodes or antinodes is half a wavelength.

Calculate the wavelength based on the amount of space between them, and then compare it to the value you expect according to the following equation:

$$\lambda = \frac{c}{f}$$

Eq. 5-1

$c = 3.0 \cdot 10^8$ m/s (speed of light), $f = 9.35$ GHz (transmission frequency)

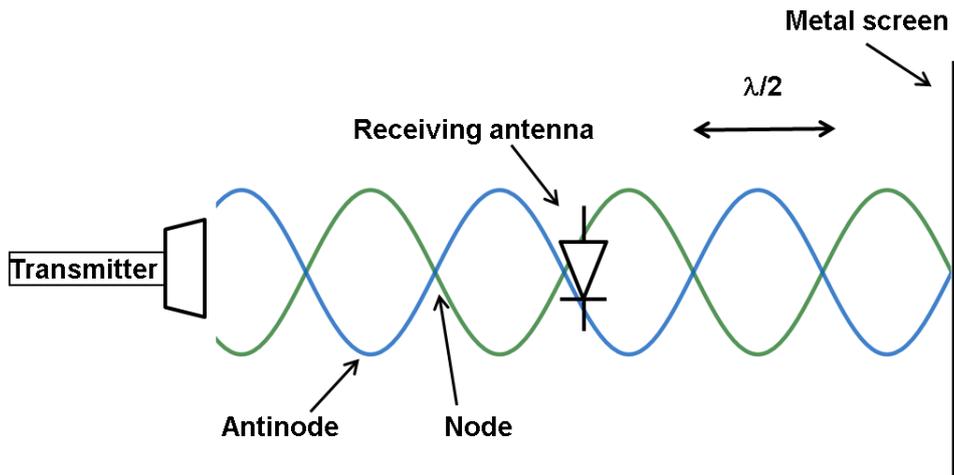


Fig. 5-3 Standing waves

Result: $\lambda(\text{experimental}) =$

$\lambda(\text{with Eq 5-1}) =$

5.2.5 Shortening of the wavelength in a medium

Position the receiver in a wave node as in experiment 5.2.4. Then put a medium (such as a plastic cuboid) into the wave field. The receiver is then no longer in the node. Move the metal plate towards the transmitter again to set a minimum and measure the displacement D .

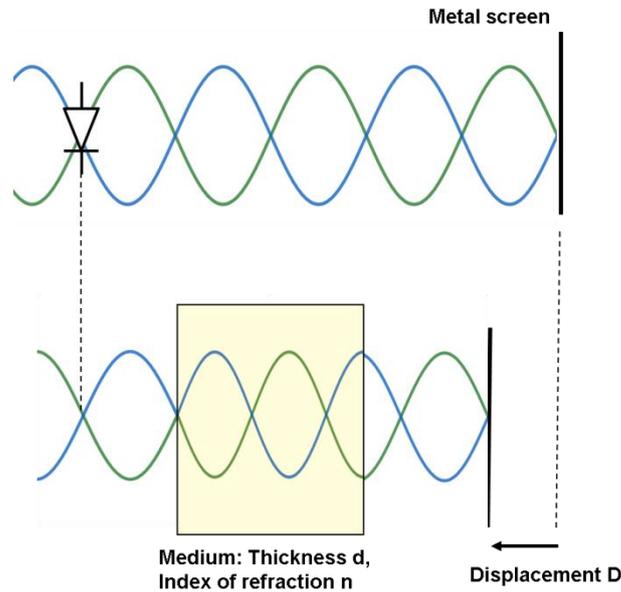


Fig. 5-4 Waves in a medium

Explanation

In a medium, the speed of light decreases compared to the value in vacuum, which also reduces the wavelength (see chapter 4.2.3)

The refractive index of the medium can be calculated using the following consideration: In the medium (thickness/length d) there is a path difference for the waves when compared to the propagation in air. This path difference is compensated by the displacement of the metal plate D .

It is described by the equation $D = nd - d = d(n - 1)$, which implies for n :

$$n = \frac{D}{d} + 1 \tag{Eq. 5-2}$$

Using this equation, calculate the refractive index of the medium.

Result: $n =$

Reference value: $n_M = 1.6$ for plastics

6 The Earth's Atmosphere

6.1 Energy Transfer and the States of Matter

6.1.1 Theory

We know water very well in its three states of matter: **solid** (e.g. as ice cubes), **liquid** (e.g. rain or what comes usually out of the tap) and **gaseous** (e.g. water boiling off a pot - this water we cannot see, but we know it's there when water drops are forming at the lid). But how is it possible for a matter as water to change between these three states?

This we can discover easily in our kitchen at home. Let's assume we put an ice cube into a pot and heat it up. It will eventually melt to become liquid water and upon heating it will finally vanish from the pot to become gaseous water. The only thing the water needed for this transformation was the heat, or let's say "energy", provided by the hotplate.

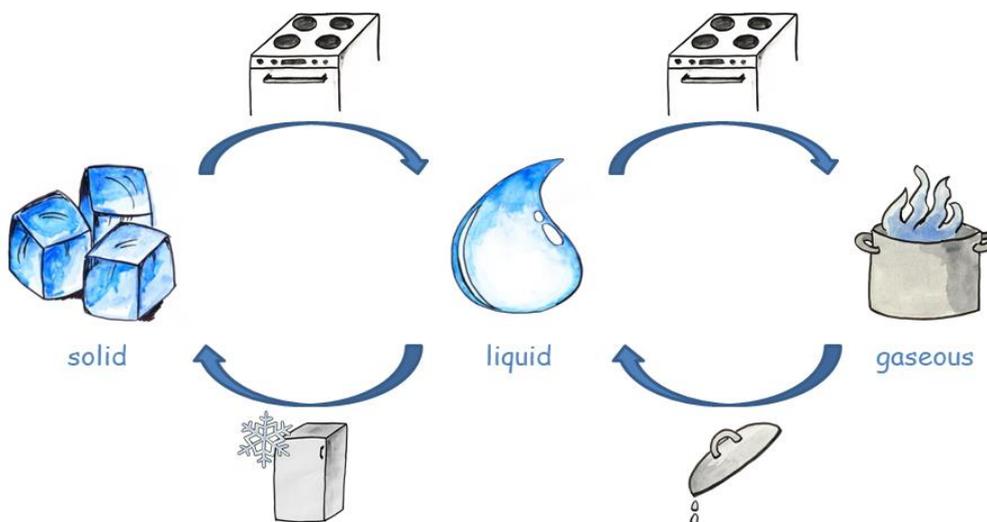


Fig. 6-1 States of matter.

The energy was given by the hot plate into the water, which contains it from then on. Liquid water contains more energy than solid water and gaseous water contains the most energy. But now it becomes tricky: The energy, which was put into the water in order to change its state of matter will come out again, when the state changes back! This we can feel when we hold a lid above a pot with boiling water inside. The water-gas will form liquid water at the lid, it condenses. While this proceeds the lid will become warmer and warmer, because the water gets rid of the energy which was previously necessary to reach the gaseous state. In order to re-transform these condensed waterdrops into ice, we can put the lid in the freezer. The freezer will take away the residual energy from the water to enable the transformation into the solid state. The energy will come out behind the freezer, where it is always warm.

By having a closer look at the molecular level, we can understand this. Let's assume a single water molecule looks roughly like a small ball. In the solid state these water balls are well ordered, like people sitting on stools in an audience. When changing to the liquid state, the balls start to move, like the audience getting up after a show for example. This movement is only possible because of energy provided to the balls or afforded by the people. Or - differently said - the more energy particles contain, the faster they move.

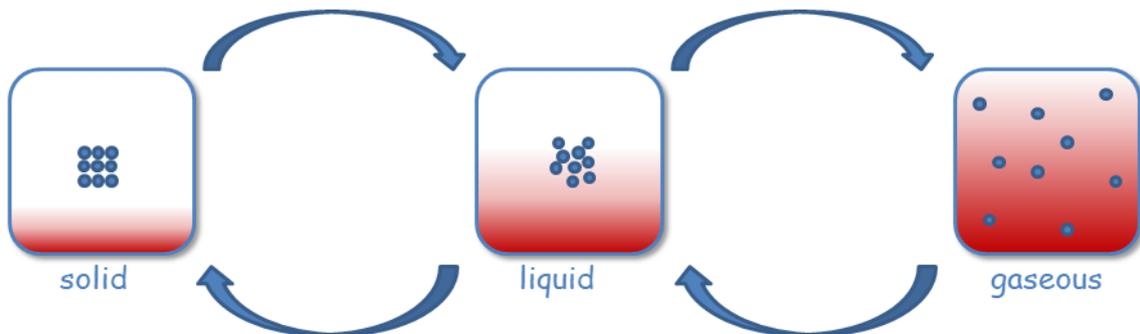
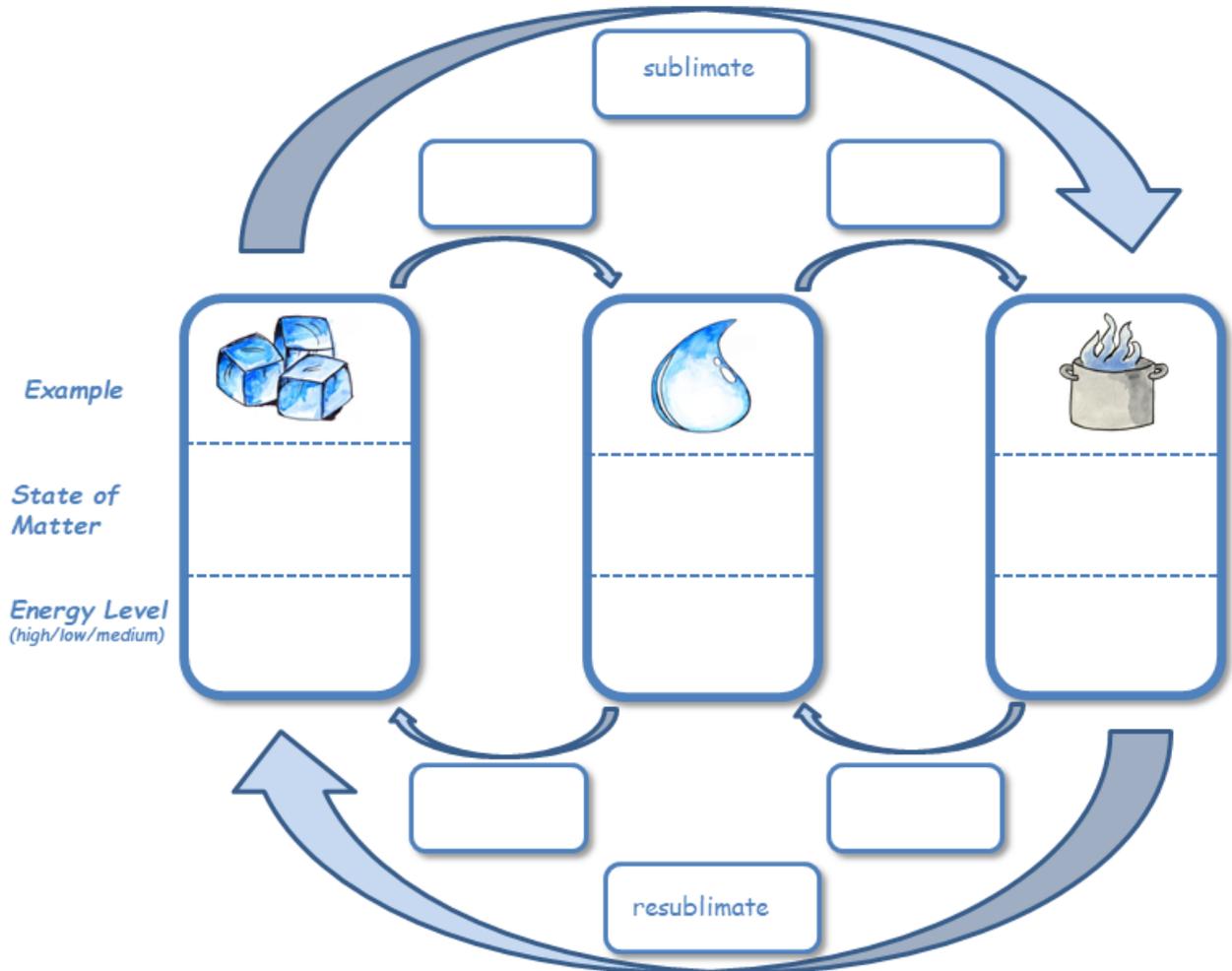


Fig. 6-2 Particle model of the states of matter. The red color depicts the relative energy level of the particles.

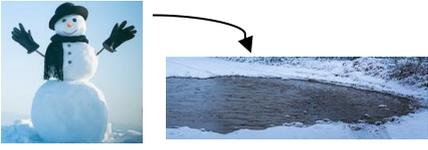
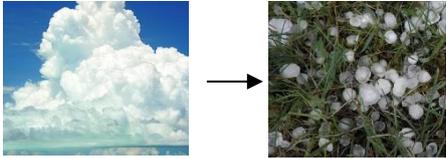
On our planet, the same things are happening. Sun-energy melts icebergs, which take the energy and become liquid water of the ocean. The liquid water of oceans or lakes can store even more sun-energy to become gaseous water in the atmosphere. In the cold atmosphere in turn, water will lose energy (because the cold surrounding will take the energy) and condense to water droplets. If there are enough droplets together, we call it a cloud. From the clouds the water can fall back to the earth as rain. In cold areas the water loses again energy and will eventually form icebergs. This is how water stores and loses energy of the atmosphere simply by changing its states of matters.

6.1.2 Exercise

1. Read the Text and fill in the gaps in the scheme below.



2. Describe which transition of states of matters is happening. Is the energy-level of the water rising or decreasing? (Be careful, the last one is a trap 😊) Picture source: www.pixabay.com or own production.

Process in Nature	State of Matters changes from ... to ...	Technical Term	Energy-level of the water rises(↑)/decreases(↓)
	<i>solid to liquid</i>	<i>melting</i>	↑
			
			
			
			
			
			
			
			

6.2 Layers of the Atmosphere

The atmosphere, which makes life on our planet possible, is made of several layers. These layers are mostly determined by their temperature, which differs a lot between the earth surface and the interplanetary medium. Between the layers only very few material transports are happening and the border layer between them are called "pauses".

In Fig. 6-3 you see a true to scale scheme of the atmosphere. The temperature change is not as usually shown as bent curve but as coloured bar in the middle in which the colour depicts the relative temperature.

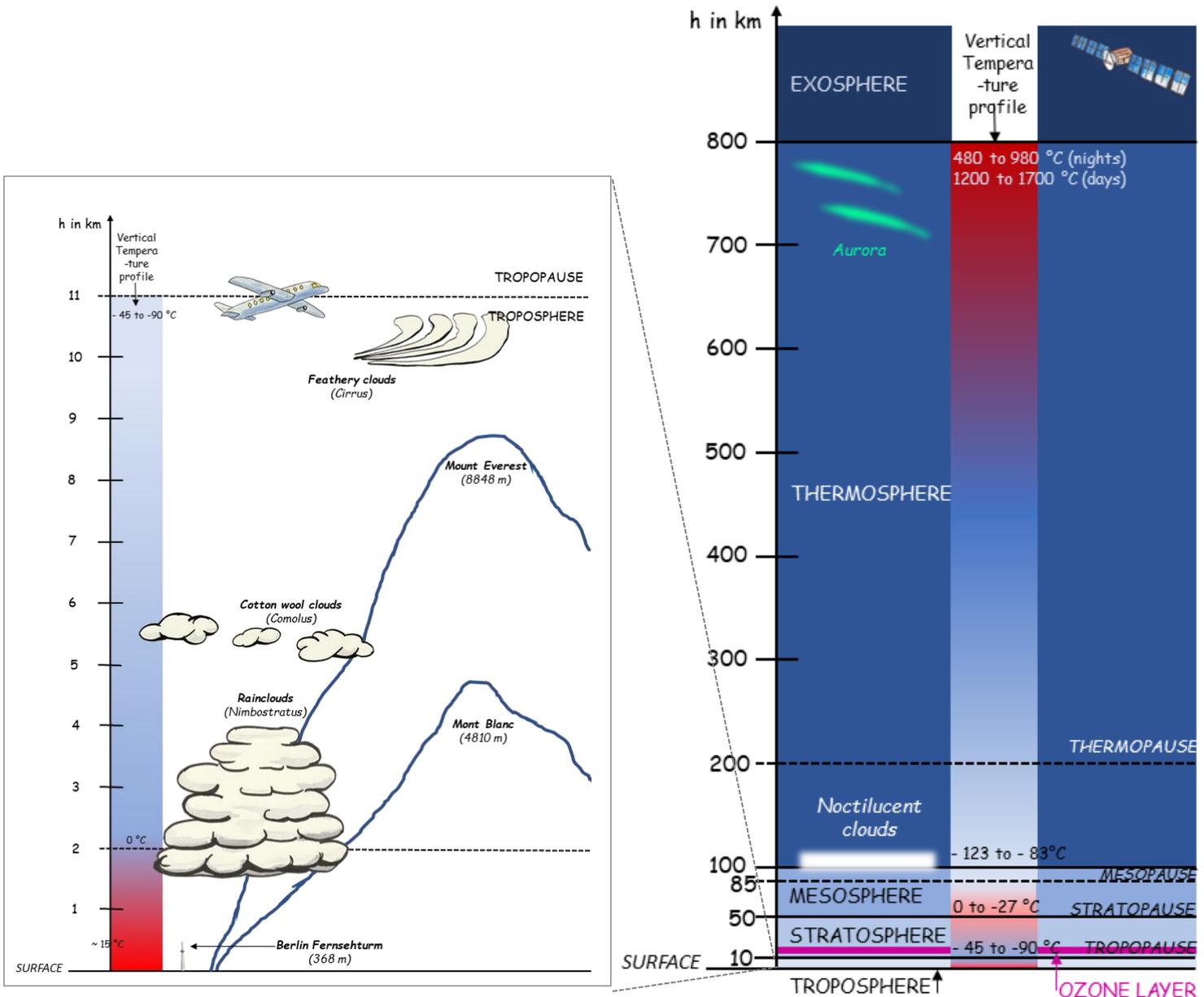


Fig. 6-3 Layers of the atmosphere.

Closest to the surface is the **TROPOSPHERE**. With a height of approx. 8 km at the poles and 18 km at the equator. This is not very high, if we consider that e.g. Berlin roughly extends to 30 km. The temperature near the surface is in average 15 °C and starting from there, it

decreases with increasing height until at the end of the troposphere -45 to -90 °C are reached. If you ever climbed up a mountain, even a small one, you might have felt that the air was cooler than in the valley. Or, since this is the maximum flight height of common passenger airplanes, you might have noticed ice forming on the windows of an airplane during flight. For those, who want to understand why the atmosphere is cooled down with increasing height, are recommended to look up "adiabatic lapse rate" in advanced literature.

Since 90% of all atmosphere mass (cf. Chapter 1.2) is found in the troposphere, here the weather is happening. Clouds, except for the noctilucent clouds forming at about 85 km height which are clusters of ice crystals, are formed in the atmosphere. They differ a lot in shape and extension.

The **STRATOSPHERE** starts, when the temperature rises again due to photolytic /chemical processes in the ozone (O_3) layer which produce heat. Here, the cooling with increasing height is overrated by the effect of the chemical processes. Thus, the air in the stratosphere heats up to 0 to 27 °C until a height of 50 km.

However, after the heating effect of the ozone in the stratosphere, at 50 km the **MESOSPHERE** starts and the air is again cooling down with increasing height. Within a height of approx. 85 km the minimum temperature of -123 to -83 °C is reached.

Here, the temperature starts rising again through the mesopause and the **THERMOSPHERE** until at a height of 800 km the **EXOSPHERE** starts, which slowly becomes the interplanetary medium. The temperature rise again is caused by chemical processes such as photolysis of nitrogen (N_2) and oxygen (O_2). These processes set a high amount of energy free so that temperature from 480 to 1700 °C (!) are reached. However, this temperature only reflects the speed of the particles. Since there are only very few of them, you would not "feel" the temperature if standing outside there.

By the way, mesosphere and thermosphere are also called **IONOSPHERE**, since here ionization of molecules is happening. Sometimes we see this as the polar lights, the aurora.

6.3 Pressure and the Barometric Height Formula

6.3.1 Theory

Why can the atmosphere apply pressure on the earth surface? This is possible because the atmosphere is not empty. Only not seeing air, doesn't mean it's empty. It is full of molecules, such as Oxygen (O_2) and Nitrogen (N_2) or water vapor (H_2O). Since these aren't solid or liquid matter, light doesn't reflect on their surface thus our eyes are not able to detect them. If the water vapor condenses and forms liquid drops in the air, light can be reflected, and we see it as fog or as clouds.

However, all these gaseous molecules of the atmosphere are attracted by the gravitational force of the earth. This is easily demonstrated by weighting an empty balloon and weight it again after blowing it up (Fig. 6-4). Doing this, you will see that the blown-up balloon is heavier than when it was empty. Obviously, air has weight.



Fig. 6-4 Empty and full balloon on a scale. The full balloon is about 3 g heavier than the empty one.

Attracted by the gravity field of the earth, most of the molecules will collect close to the earth surface. This is the reason why the height of the troposphere reaches its minimum at the Poles (8 km), where gravity has its maximum strength, and vice versa on the Equator. As we learned in Chapter 1.2 before, about 90% of all molecules are collected in the very thin shell of the troposphere. We can compare this with a suspension of, e.g. sand in water. When we leave it standing after stirring, sand starts to collect at the bottom of the glass due to gravity. It's very similar for the molecules of the atmosphere. However, they never completely "lay down" at the surface since they are much lighter than sand and they never stop to move.

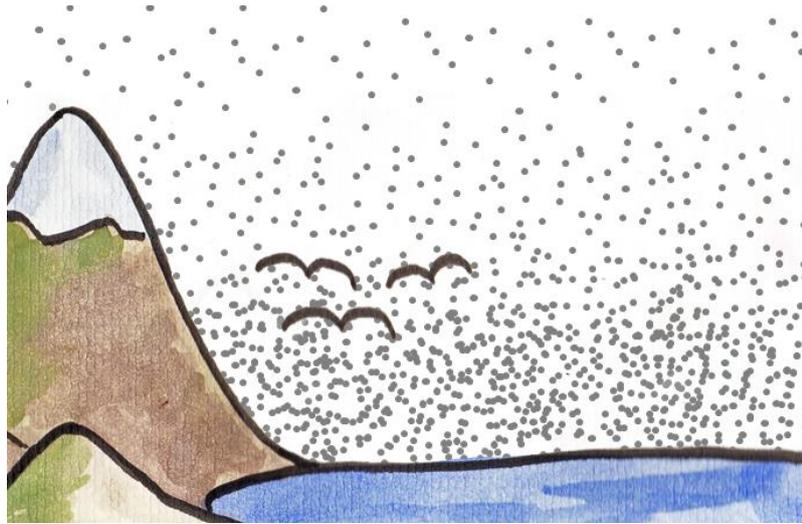


Fig. 6-5 Gas molecule collect at the earth surface due to gravity, thus causing higher air pressure.

Thus, the molecules close to the earth surface apply a higher air pressure than these on a high mountain, because there are more of them. This is comparable with the pressure water applies on a diver. The deeper he dives, the higher the water pressure will get around him. If he was diving very deep, it wouldn't be healthy for him to come back to the surface very fast. He has to come up slowly so that his body will get accustomed again to the much lower pressure on the surface.

Also, a mountain climber in large heights will need additional oxygen, because there are not enough oxygen molecules for him to breathe due to the lower pressure. For the same reasons, when you go for hiking or climbing, you can use an altimeter watch, equipped with a nano-sensor of pressure, to know the altitude of your path.

In general, we can say the air pressure decreases with increasing height. The height-dependence of the air pressure can be described by the **temperature-independent barometric height formula**:

$$p(h) = p_0 \cdot e^{-\frac{\rho_0 g h}{p_0}} \quad \text{Eq. 6-1}$$

Were $p(h)$ is the pressure in a chosen height, p_0 the pressure on the surface (at the sea level; $p_0 = 101325 \text{ Pa}$), ρ_0 the density of the air on the surface ($\rho_0 = 1,16 \text{ kg/m}^3$), g the gravity-constant of the earth ($g = 9,81 \text{ m/s}^2$) and h the respective height over the surface.

Since the function of the air pressure over the height is not a linear one but an exponential correlation, the pressure decreases very fast with increasing height.

This temperature-independent formula is just an approximation, since the air pressure is connected to the air density, which itself changes with changing temperature. Thus, to be more precise, we should also consider the temperature which differs a lot on the way through the atmosphere, as we have learned before.

However, the results obtained by appliance of the temperature-independent formula are mostly often precise enough. Weather phenomena in the troposphere cause strong changes in the air pressure - we call an area of lower air pressure than usual a low-pressure region ("low"), which is

often associated with cloudy or even wet weather. In turn, an area of higher air pressure than usual, is called a high-pressure region ("high") and brings usually sunny weather.

At the end of this chapter we shall not forget to discuss briefly the different units that are commonly used for (air) pressure.

Physically, pressure (p) is defined as "force (F) per area (A)" ($p = F/A$). Therefore, the unit must be referring to the international unity system (SI) "Newton per square-meter" ($[p] = 1 \text{ N/m}^2$). To introduce a shorter expression, 1 N/m^2 was set equal to 1 Pa (Pascal) in honour to the French scientist Blaise Pascal who lived from 1623 to 1662. Another unit conferring to the SI-system is "bar", where 1 bar is equal to 100000 Pa (or 1000 hPa or 100 kPa).

Since the air pressure was not only relevant for physicist but also for meteorologists, also the normal pressure on the earth surface became a standard value. It was defined as 1 atm (atmosphere). The "atmosphere" does not correspond to the SI system and 1 atm is equal to approx. 1.013 bar.

6.3.2 Exercises

1. Air pressure is often measured in "Hectopascal" (hPa) or "Millibar" (mbar). Calculate how much the atmosphere pressure is in hPa and in mbar.
2. A car tyre is inflated to a pressure of approximately 2.5 bar in addition to the normal air pressure. How much is this in Pascal?
3. Look at the weather card below and decide, if there is a high or a low over Brest. In which unit are the numbers at the isobars (thin black lines; "isobare" means line of constant pressure) given?

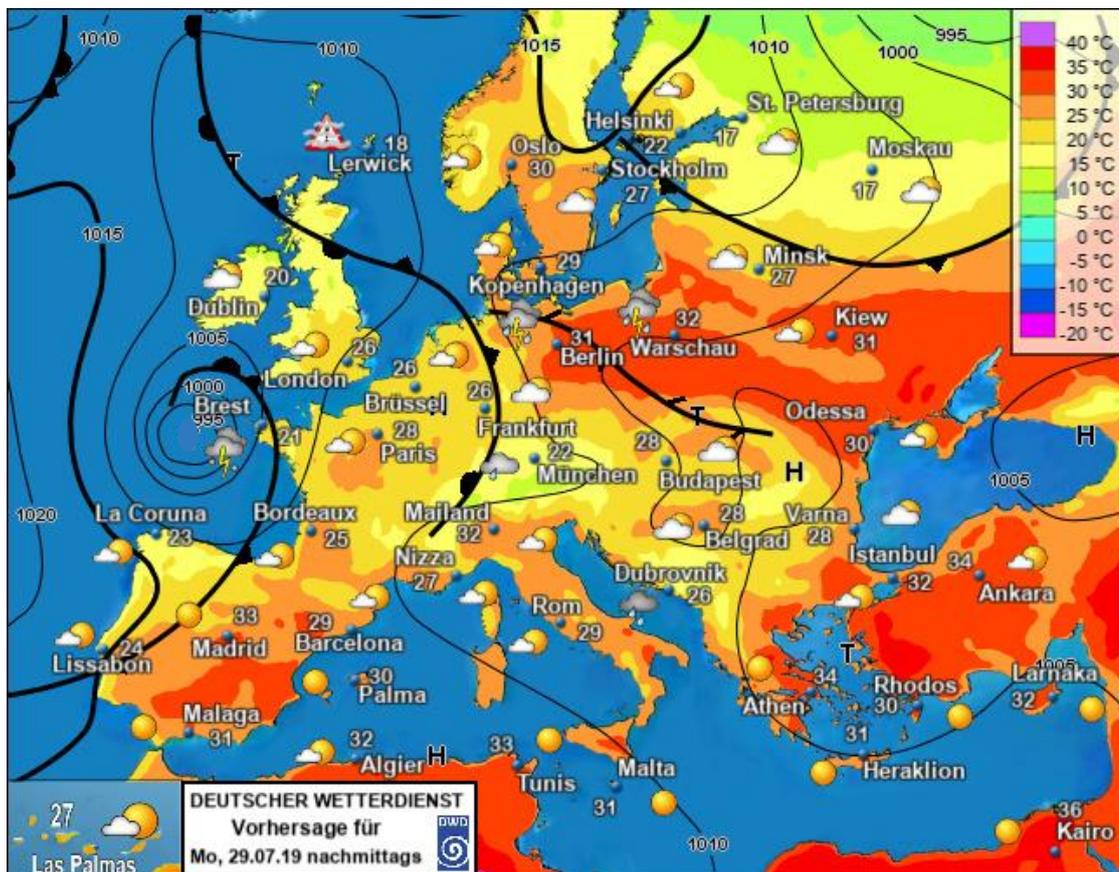


Fig. 6-6 Weather map showing high and lows of temperature (colors palette) and pressure (black isolines).

3. Calculate the air pressure in Berlin (~32 m above sea-level), for the Fernsehturm in Berlin, the top of the Mont Blanc and the Mount Everest and where the noctilucent clouds are. The data you need you will find in chapter 6.2.
4. In which height is the pressure only half the value than it is at ground level?

6.3.3 Experiments with the Pressure Sensor of a Smartphone

You need a proper App (e.g. phyphox) installed on your smartphone. Of course, your smartphone needs to be equipped with a pressure sensor, too. 😊

Open in the app the menu "Pressure" in order to measure the air pressure.

Now measure the air pressure in different situations:

- Running stairs up and down
- Going by elevator up and down
- Hiking up a hill
- Putting your Phone in a well closed plastic bag and put it in a sink filled with hot or cold water. *Be sure that your phone is water-tight!!!*

... (find more situations where you can record a change in the air pressure)

If you are not able to perform the experiments (maybe you are in a bungalow a flat land and your phone is definitely NOT water-tight), you can use the exemplary data offered below.

Exemplary Data from Berlin, recorded on 29/07/2019:

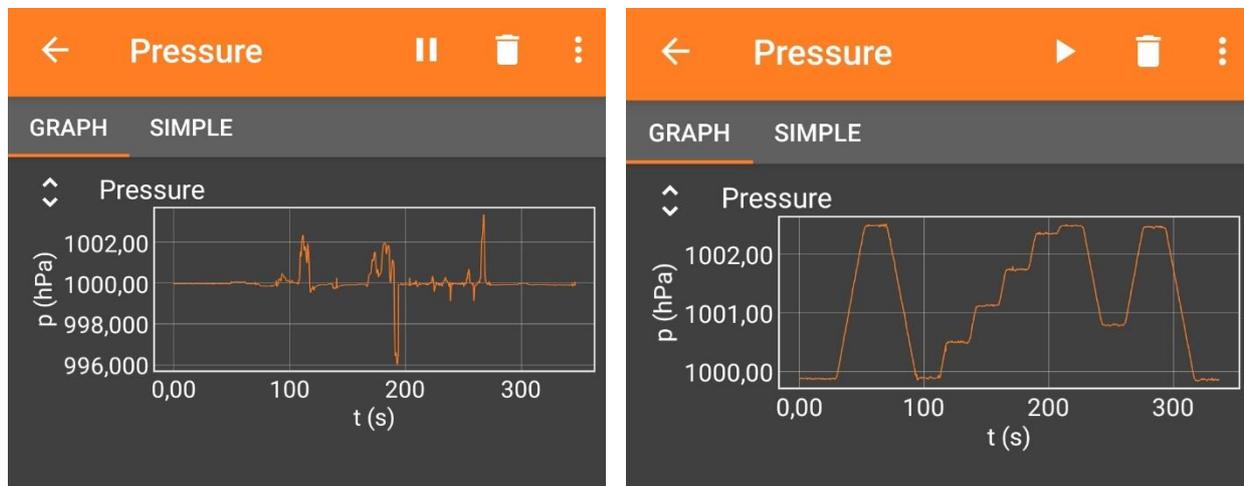


Fig. 6-7 Pressure sensor record of mobile under water (left) and in the elevator (right).

A: Under water

1. When was the phone put in a sink with cold water and when with hot water?
2. Why is it for the measurement important to close the plastic bag properly? Why cannot pressure change be measured, when the bag is left open?
3. How might the weather have been on the 29th July 2019 in Berlin? (See map in Fig. 6-6)

B: In the elevator

The measurement was proceeded in a house with 8 floors, plus ground level (level 0). The entrance

is a little bit below the ground level (level -1).

1. The elevator was moving between the entrance and the 8th floor. Where was the measurement started? Explain your decision.
2. Explain, on which levels the elevator stopped between $t = 100$ and $t = 250$ seconds.
3. Investigate, if there is a linear or exponential dependence between pressure and height observable. Explain your findings.
4. The density of the air was about 1.149 kg/m^3 on that day. Calculate the approximate height of the house by applying the barometric height formula.

6.4 Clouds and how They Form

6.4.1 Theory

At the beginning of each cloud, there is water vapor in the air. As vapor, the water molecules move as gas without any contact to each other. However, when there are too many of them to move individually, they form a small aggregate, which means that they collect in a small group in which they have contact to the molecules next to them (see also chapter 6.1). In other words, the water is condensing. If the molecules of the water vapor feel comfortable, depends on the temperature and the pressure. At high temperatures there can be a higher amount of water vapor in the air than at low temperatures. At high pressure, there can be more water vapor in the air than at low pressure. Thus, a "high" is often cloudless, because the air can carry more water vapor without inducing condensation.

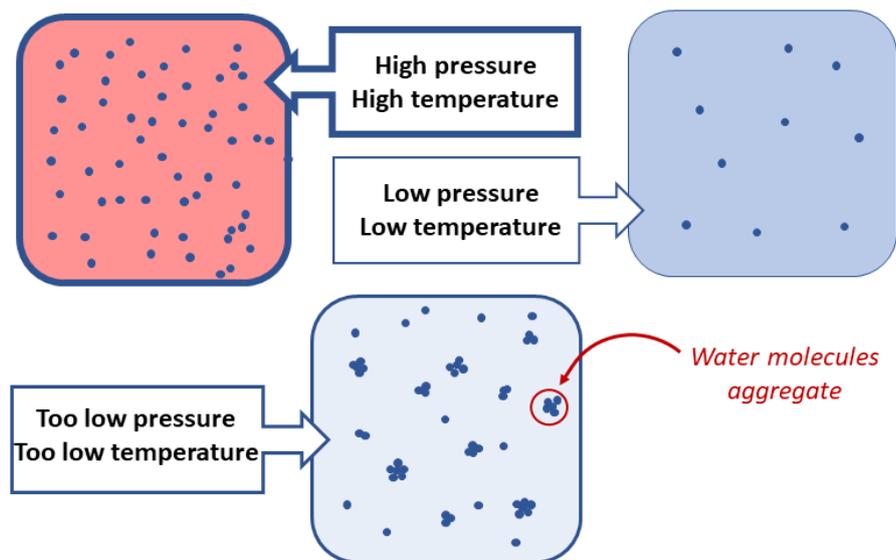


Fig. 6-8 Air at high pressure/high temperature carries a lot of water vapor and air at low pressure / low temperature carries only few water molecules. If the conditions are e.g. too cold, the water molecules aggregate.

Since this project aims to measure the atmospheric water vapor, we will have a closer look at the humidity - the amount of water vapor in the atmosphere.

Now we need to familiarize with some concepts related to the air's WV content and humidity and to look at different ways to express them. The term humidity can describe the amount of water vapor in the air. In principle, warm air has a greater capacity for water vapor than does cold air; hereafter we will see why. The water vapor content (humidity) inside an air parcel can be expressed in a number of ways.

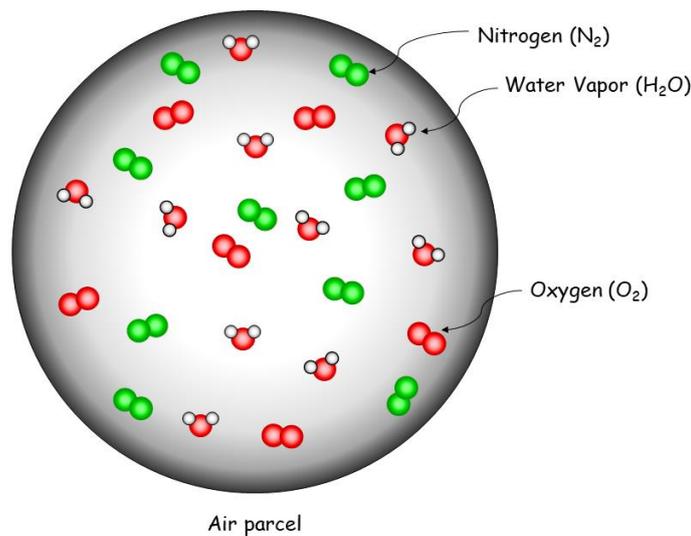


Fig. 6-9. A parcel of air containing water vapor, nitrogen- and oxygen-gas.

Absolute Humidity

Suppose we enclose a volume of air in an imaginary thin elastic container as could be a balloon, a parcel Fig. 6-9, in principle we might be able to determine the absolute humidity of the air, that is, the mass of water vapor in a given volume of air, which can be expressed as:

$$\text{Absolute Humidity} = \frac{\text{Mass of water in the parcel}}{\text{Volume of the parcel}}$$

Therefore, absolute humidity represents the WV density (mass/volume) in the parcel and, normally, is expressed as grams of water vapor in a cubic meter of air. For example, if the water vapor in 1 cubic meter of air weighs 25 grams, the absolute humidity of the air is 25 grams per cubic meter (25 g/m³). A rising or descending parcel of air will experience a change in its volume, the balloon expands or shrinks, because of the changes in surrounding air pressure. Consequently, when a volume of air fluctuates, the absolute humidity changes even though the WV content has remained constant. That's why the absolute humidity is not routinely used in meteorology.

Relative Humidity

In meteorology, relative humidity (RH) is the most used parameter to describe atmospheric moisture. The concept of relative humidity is a bit tricky because it does not indicate the actual amount of water vapor in the air. Instead, it tells us how close the air is to being saturated. RH is the ratio of the amount of water vapor actually in the air to the maximum amount of water vapor required for saturation at that particular temperature (and pressure). It is the ratio of the air's water vapor content to its capacity;

thus:

$$\text{Relative Humidity} = \frac{\text{Water Vapor Content}}{\text{Water Vapor Capacity}} = \frac{WVP}{SWP} \times 100\%$$

RH is given as a percent. Air with a 100 percent relative humidity is said to be saturated. Air with a 50 percent relative humidity actually contains one-half the amount required for saturation. RH can even become greater than 100 percent; in this case, we call it **supersaturated air**. Now we might understand that a change in relative humidity can be induced in two main ways: 1) changing the air's water vapor content; 2) changing the air temperature. In conclusion, with no change in temperature, adding water vapor to the air increases the RH; removing water vapor from the air decreases the relative humidity.

Dew Point

The dew point (DP) is an important variable used in predicting the formation of dew, frost, fog. DP represents the temperature to which air would have to be cooled (with no change in air pressure or WV content) for saturation to occur. Since DP is a temperature, it is given as degrees Celsius or, in SI, Kelvin (K). As atmospheric pressure varies only slightly at the earth's surface, the dew point is a good indicator of the air's actual WV content. A high DP indicates high WV content and vice versa. That's why some empirical laws have been proposed to assess the air's WV content from the DP.

Now, we can understand why clouds are usually formed at the sky and not directly over the ocean, for example. The air over the ocean is supposed to be rich of humidity, but, since it is relatively warm, it can hold a lot of water vapor. When the air rises up, it cools down (see chapter 6.2) and the relative humidity becomes larger and larger until it reaches 100% and small aggregates of water will form to become larger droplets to form clouds which will eventually become so large that they will fall down to earth as rain.

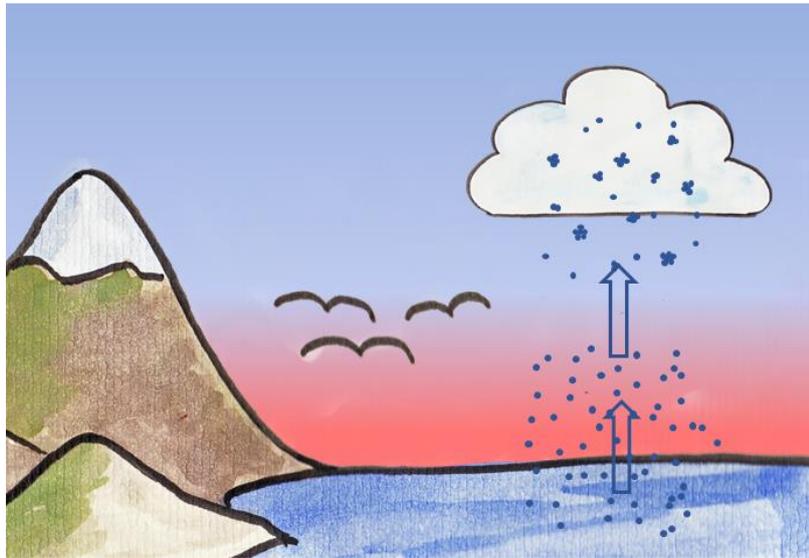


Fig. 6-10 Water evaporates into warm air and rises while the temperature of the atmosphere decreases. Eventually the water molecules aggregate to form clouds.

Notice: When the relative humidity on the earth surface is high enough, the cloud will directly be formed around us. This we call "fog". 😊

Also, when two air masses of different temperature mix up, clouds can be formed due to the new temperature which results in air packages oversaturated with humidity.

However, it's not only temperature and pressure influencing the formation of clouds. The initial aggregation is very tough work for the water molecules, because the relative surface of the aggregate is very high, thus unstable. It's much easier for water to aggregate on another small particle, such as carbon black, mineral dust, ashes, sulfuric acid and many more. In general, we call these very small particles "aerosols" and they can play a role as "condensation nuclei" (so-called because water vapor condenses on them).

If there are only very few aerosols in the air, it can happen, that the water is not able to aggregate, even though it is already oversaturated. When an airplane flies through such oversaturated air, it will blow aerosols in the air causing the water vapor to condense spontaneously to leave a vapor trail.

Of course, that's not the only mechanism how vapor trails can form. They also appear in unsaturated air since the airplane sets, besides carbon black, also additional water vapor, hot air and sulfuric acid precursors free. Especially differences in the local pressure will lead to condensation of water.

Clouds appear in very different types (Fig. 6-10). For example, there are the fluffy cotton-wool clouds, in which you can see faces or creatures when lying on a field in summer looking up the sky. Or the feathery ones that look so light and fragile or the bulky rain clouds. But have you ever thought about their drop constitution or the height in which they appear? You will see, there are huge differences leading to very different physically behaviour of the clouds respectively.

Thunderclouds (cumulonimbus) and **rainclouds (nimbostratus)** are very similar. They both start very close to the earth surface, at around 1 km height and their droplets are big enough to be able to fall to earth as rain. The difference between them is that thunderclouds are much

higher, reaching almost through half the height of the troposphere so their upper part is located in a much colder surrounding than the rest of it (see chapter 6.2). Thus, the upper droplets get frozen and fall down through the cloud-tower. By doing this, they transfer electrons to the liquid water droplets in the cloud, which leads to a potential difference within the upper and lower part of the cloud causing discharging by lightning. Interestingly, a water drop which will fall down as rain is one million times larger than a usual cloud-droplet. Often, it is initially ice that falls down which melts on its way to the surface. If not, we call it hail.

Feathery clouds are called "cirrus" (*cirrostratus*, *cirrofibratus*, *cirrusunicus*, *cirrocumulus*). They appear in large heights about 8 - 12 km and the different types differ in look and shape, but are commonly made of ice-particles.

Horizontally layered clouds (stratus) or "high fog" have no special shape but just cover the earth uniformly. They lie very low in the atmosphere and were formed either through lifting of morning fog or through cold air moving at low altitudes over a region and need windless weather. These clouds may produce a drizzle or fine snow crystals. However, there are also stratus in higher heights around 5 km which are called **altostratus**.

The typical **cotton-wool clouds (cumulus)**, in which you can so nicely see faces or animals, develop when humid air is rising and condensing when the temperature is low enough. Consequently, these clouds appear to begin all at the same height about approx. 1 km and are flat at the bottom. Since they are densely filled with water, they show strong shadows underneath. If cumulus clouds appear a little higher at 3 - 6 km and are less dense, they are called **altocumulus**.

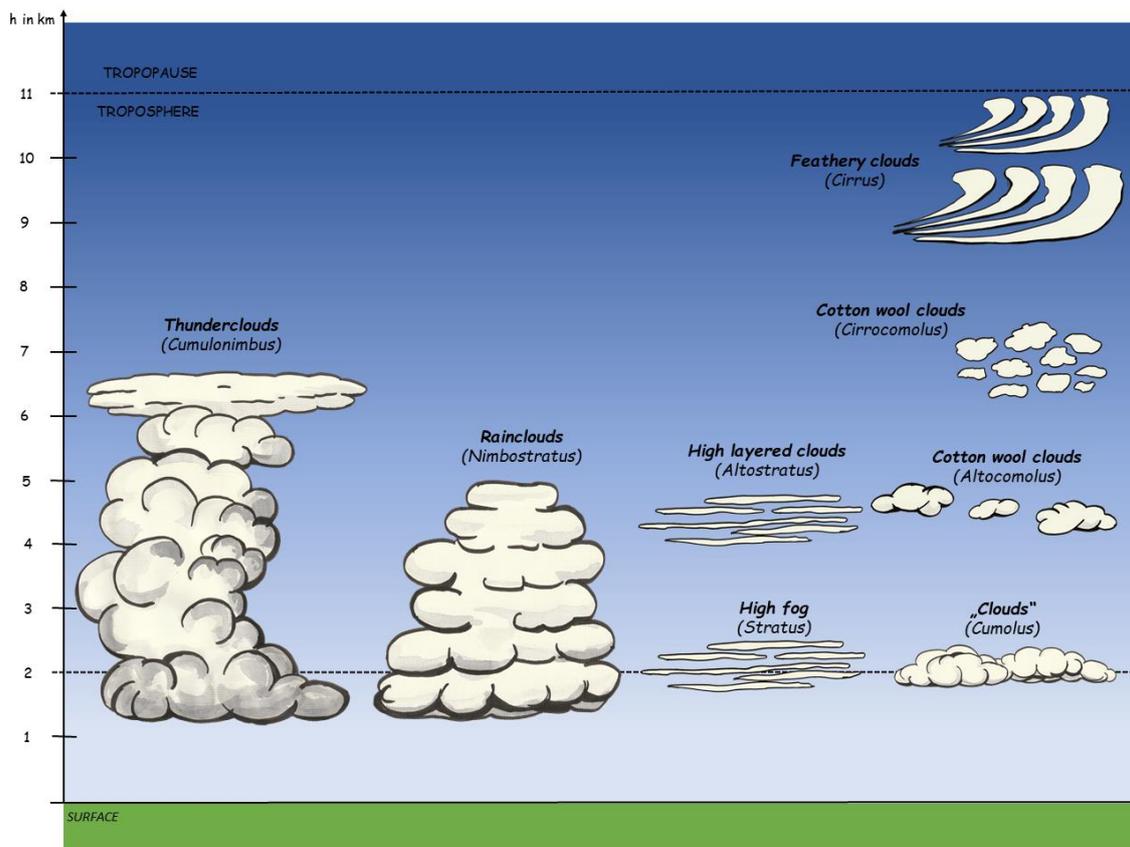


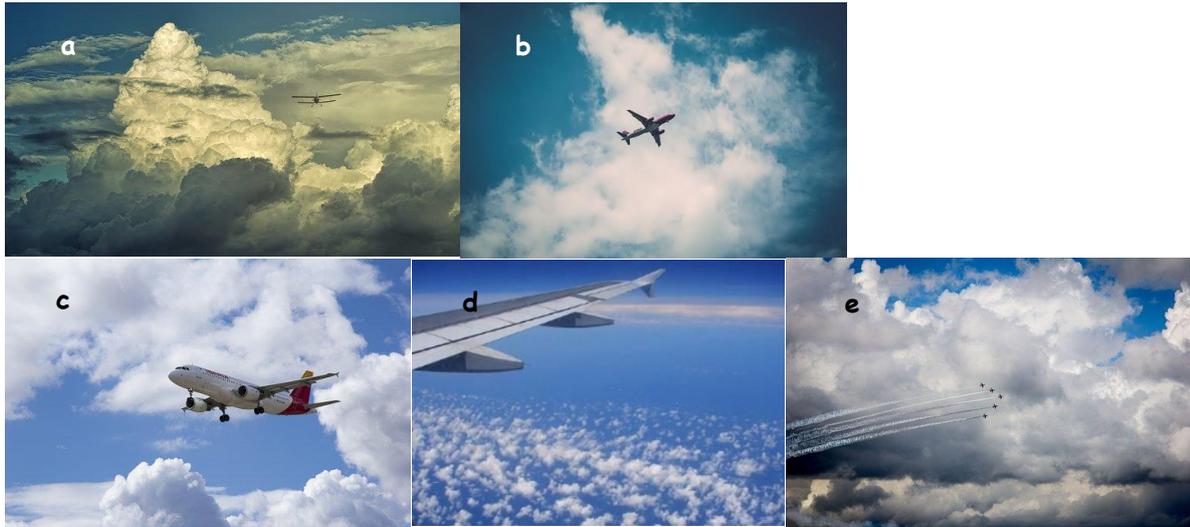
Fig. 6-11 Selection of common cloud types.

Why and how clouds are formed is of huge interest, because clouds can affect the greenhouse effect very much and in very different directions, depending on parameters such as particle size of droplets or ice crystals. Also, it is hard to predict if and how they are formed. Thus, a lot of research is done concerning this topic and this chapter offers only a very brief overview.

6.4.2 Exercise

Look at the picture(s) and guess, in which height the airplanes might fly by comparing them with the clouds around them. See answers below (upside down).

Picture source: www.pixabay.com



(a) Altitratus and Nimbostratus ~ 5 km (b) ~ 3km (Airplane is still rising) (c) Cumulus ~ below 2 km (airplane is landing) (d) Cirrocumulus - high above 6 km, presumably travel high ~ 10-12 km (e) Below Nimbostratus - below 2 km

6.4.3 Experiment "Self-Made Clouds"

Material

- Empty water bottle (plastic, 1.5 L)
- 1.2 L cold water (from the tap - without gas)
- Matches



Procedure

Fill the water in the bottle. Throw one or two burning matches inside the bottle and close the bottle fast and tight. Press with your hands the bottle very tight and let it release suddenly. What can you observe?

Repeat the pressing and releasing several times. Does it always look the same?

Open the bottle at last and press carefully a few times. What can you observe?

Explanation

1. What happens with the pressure inside the bottle when you press and release it? Explain, how the bottle-clouds can be formed.
2. Try to get any clouds without the matches and explain which role they play in order to make clouds.
3. Make the connection to "real" clouds by filling in the table below.

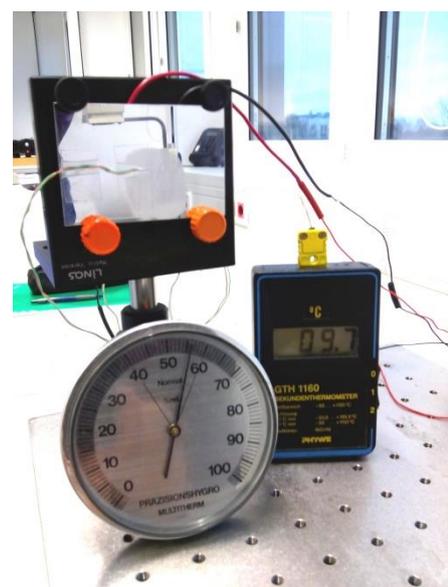
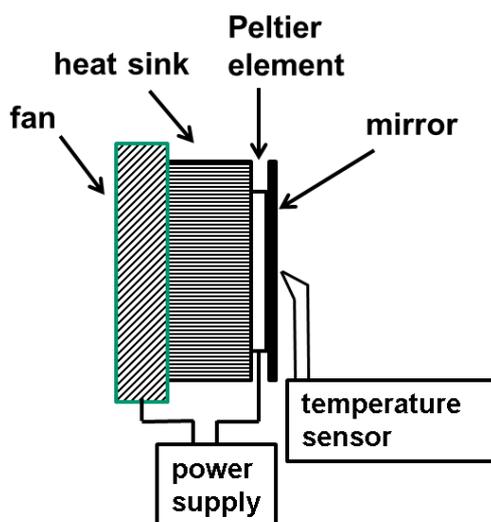
"Bottle"-Clouds	Clouds in the Atmosphere
Water	
Pressing	
Releasing	
Matches	

6.4.4 Experiment: Measurement of the Dew Point and Humidity

The dew point is defined as the temperature air must be cooled down to in order to become saturated with water vapor (wikipedia, cf. chapter 6.4.1).

In the following experiment the dew point will be measured by cooling a mirror surface. When a temperature slightly below the dew point temperature is reached, air's water vapor will condense at the surface. The resulting water condensate can be observed easily.

Experimental Setup:



Tasks:

Measure the ambient temperature with the temperature sensor (thermocouple).

$\vartheta_{\text{ambient}} =$

Connect the Peltier element and the fan with the power supply (maximum current for the Peltier element 1,0 A, voltage for the fan 8 V approx.).

After switching on the power supply the mirror will cool down constantly. Observe the surface of the mirror. When water is beginning to condense, measure the temperature with the sensor (ϑ_1). Shortly afterwards switch off the power supply and measure the temperature, when the condensed water has disappeared (ϑ_2)

$\vartheta_1 =$

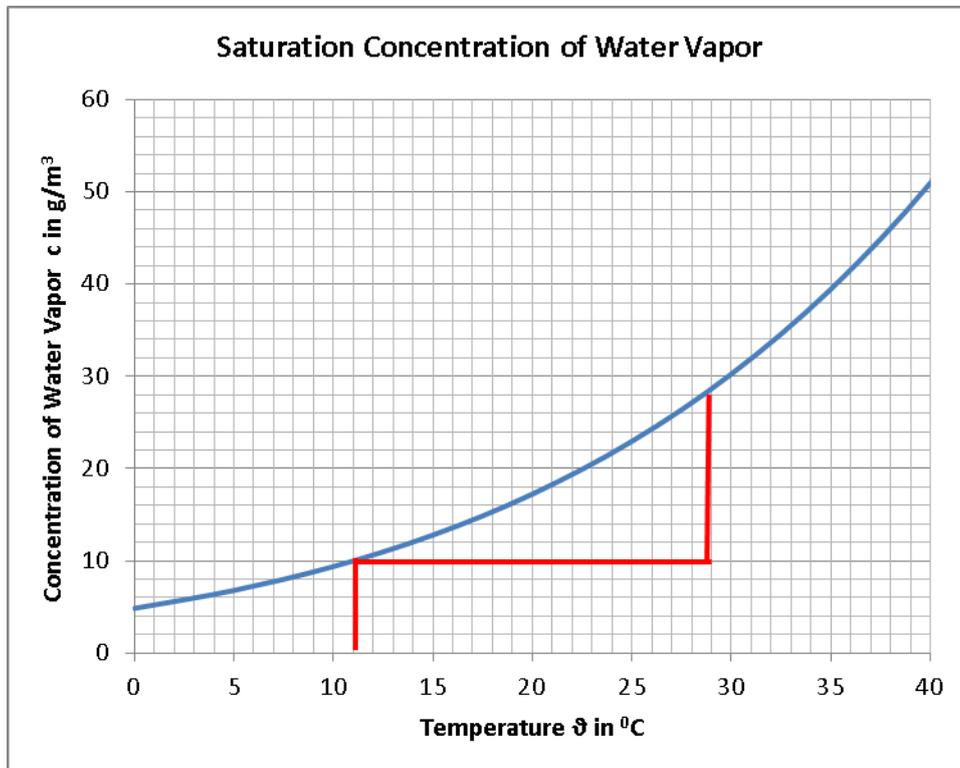
$\vartheta_2 =$

The dew point is the mean value of both temperatures. Repeat the experiment several times to get reproducible results.

Result: $\vartheta_{\text{dew point}} =$

Calculation of the Relative Humidity

From the measurement of the dew point the relative humidity can be evaluated by help of the following diagram:



Read out the saturation concentrations for the dew point temperature and the ambient temperature respectively. The relative humidity can be calculated applying the following formula:

$$\text{relative humidity} = \frac{c_{\text{dew point temperature}}}{c_{\text{ambient temperature}}} * 100\%$$

Result:

Example: red marked in the diagram: $\vartheta_{\text{dew point}} = 11^{\circ}\text{C}$, $\vartheta_{\text{ambient}} = 29^{\circ}\text{C}$

$$\text{relative humidity} = \frac{10 \text{ g/m}^3}{28 \text{ g/m}^3} * 100\% = 35,7\%$$

6.5 Incoming and Outgoing Radiation on the Earth

6.5.1 Theory

The source of all energy available on the earth is delivered by the sun. Also, fossil energy once needed sun energy when the oil still was trees. But how is the sun able to heat up the planet? Therefore, we must consider two sets of electromagnetic waves: Firstly, the incoming radiation from the sun which is mainly ultraviolet ($\lambda = 100 - 380 \text{ nm}$) and visible ($\lambda = 380 - 750 \text{ nm}$) light and secondly the light emitted by the earth. The sun also emits infrared ($\lambda = 750 \text{ nm} - 1 \text{ mm}$) light but this radiation appears not being so strong due to the high temperature of $\sim 6000 \text{ K}$ of the sun. Following Wien's displacement law, a black body of very high temperature has its maximum radiation intensity at shorter wavelengths than a black body of lower temperature, which emits at longer wavelengths. Such a black body of lower temperatures is the earth, which absorbs a part of the incoming energy from the sun for heating itself up to $210 - 310 \text{ K}$. Thus, the earth emits radiation in the infrared region ($\lambda = 4 - 60 \mu\text{m}$). In Fig. 6-12 both radiations are depicted as red and blue lines. The lines represent the behaviour of the black bodies respectively, which is an idealized behaviour. The filled areas represent the actually incoming and outgoing radiation.

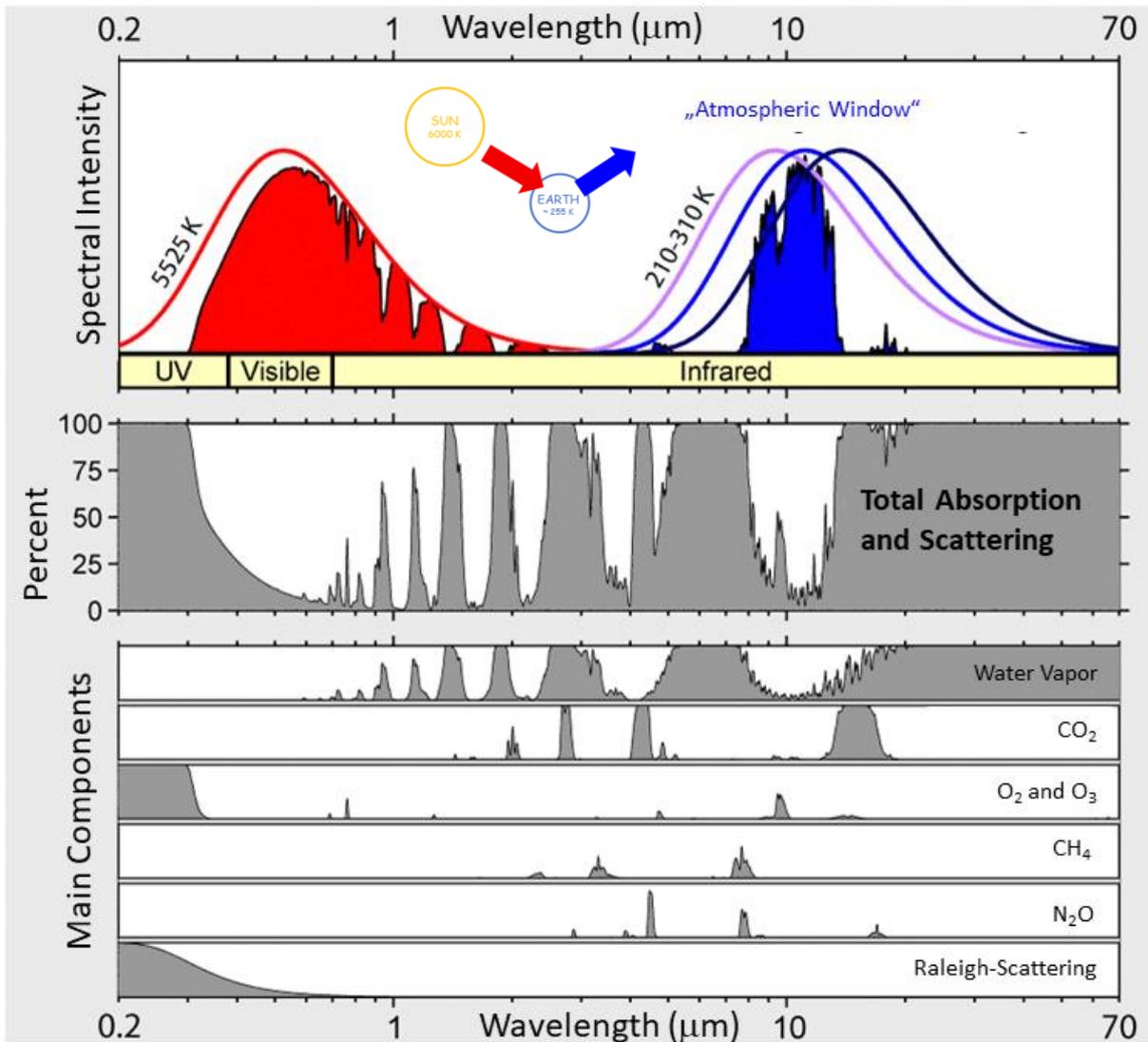


Fig. 6-12 Incoming and outgoing radiation on earth and absorption bands of the atmosphere. Modified picture based on: CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=49295181>

Radiation is mostly absorbed by molecules in the atmosphere but also scattered and reflected; which is depicted in Fig. 6-13. The very short wavelengths around 100 nm are already absorbed in the ionosphere thus never coming in touch with the atmosphere close to the surface. The highly toxic UV-C radiation ($\lambda = 100 - 280 \text{ nm}$) is fully absorbed by oxygen (O_2) in the stratosphere and troposphere, while the main part of UV-B radiation ($\lambda = 280 - 315 \text{ nm}$) is absorbed by the ozone (O_3) in the stratosphere. The absorbed radiation causes bond dissociation in O_2 and O_3 thus leading to chemical transformations thus heating up the stratosphere. However, the UV-B radiation reaches partially the earth and can cause strong sunburns on our skin as well as long-lasting tanning. UV-A radiation ($\lambda = 315 - 380 \text{ nm}$) is not as harmful as UV-C and UV-B radiation, but does also cause sunburn and leads as well to tanned skin, which is, however, not long lasting and does not have protection properties. This type of radiation reaches nearly completely the earth. Visible light is not absorbed at all. The radiation which was not absorbed in the atmosphere is partially reflected by clouds and partially by the earth surface (e.g. from snow- or ice-covered areas). By the way, the back-reflection of radiation by atmosphere and surface is also called "albedo". In total, about 50% of the radiation which was send from the sun is reaching the earth where they are absorbed and transformed into heat/infrared radiation.

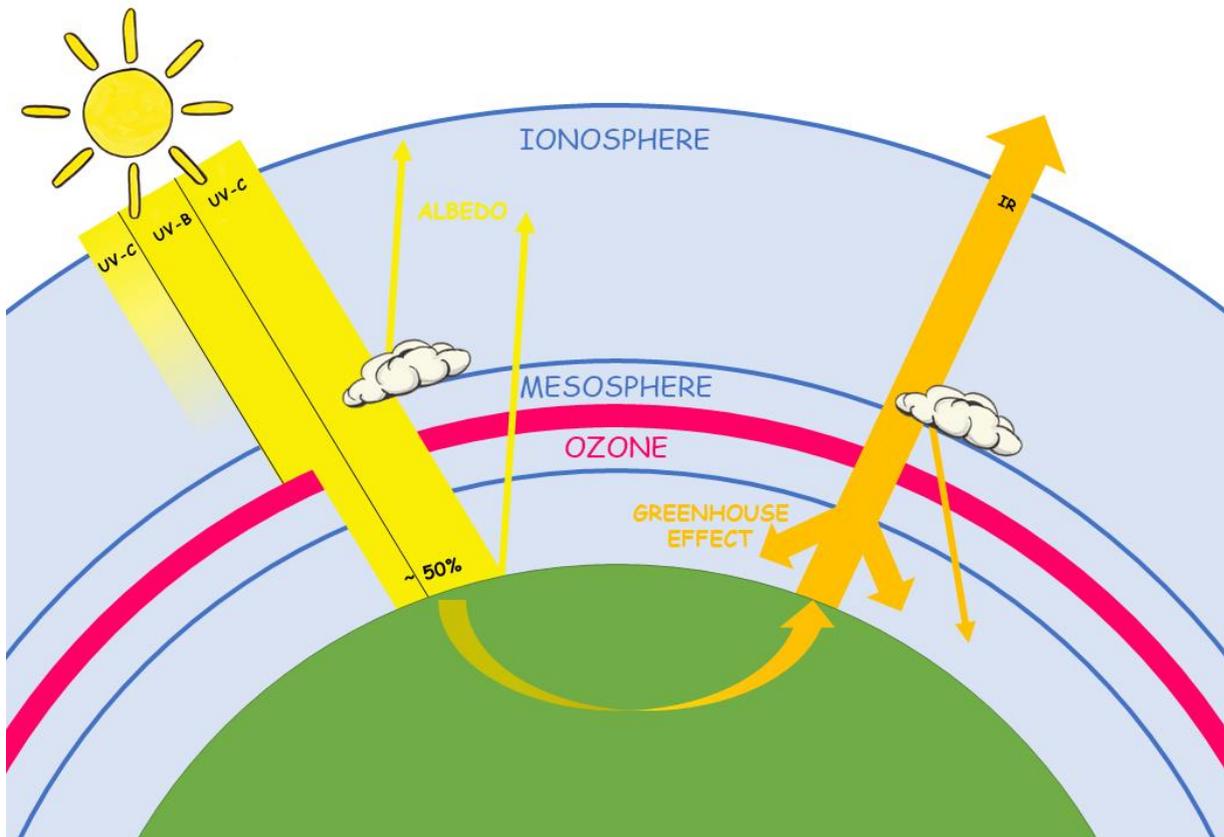


Fig. 6-13 Incoming and outgoing energy on the earth.

Without the atmosphere, the earth would send the produced heat directly into space. But on its way to space, it passes the gases of the atmosphere and some wavelengths cause vibration and rotation of the molecules without destroying them (Fig. 6-12). Or, in other words, the heat goes into the molecules which finally send it back to earth. Molecules with absorption properties of infrared radiation are called "greenhouse gases", because they keep the heat inside the atmosphere just like the roof of real greenhouse in a garden. In addition to the greenhouse gases, also clouds are able to reflect heat back to earth. You might have remarked that during cloudy nights the air does not cool down as much as it does in starry nights.

6.5.2 Exercises

1. Have a closer look at the schemes in Fig. 6-12.
 - a. Which is the most effective greenhouse gas? Explain your answer. This gas contributes approx. 60% to the natural greenhouse effect.
 - b. Find a definition for "atmospheric window"

2. Why is it important that sun blocker offers both UV-A and UV-B protection?



3. Radiation is recorded in lots of varying wavelengths (cf. chapter 6.5). Elaborate an overview about the relevant radiation passing the atmosphere with their range in different units. Use the table below.

The following formula might be useful:

$$E = h \cdot c \cdot \frac{1}{\lambda} = h \cdot f$$

E = Energy; h = Planck-constant = $6,626 \cdot 10^{-34}$ Js;
 c = Speed of light in vacuum = $2,998 \cdot 10^8$ m/s²; λ = Wavelength; f = Frequency

Radiation Type	Wavelength (from ... to ...)			Energy in	Frequency in MHz
	in nm	in μ m	in mm		
UV-B					
UV-A					
Vis					
IR					
Atmospheric window					
Galileo E6 (see picture below)					
Galileo E1 (see picture below)					

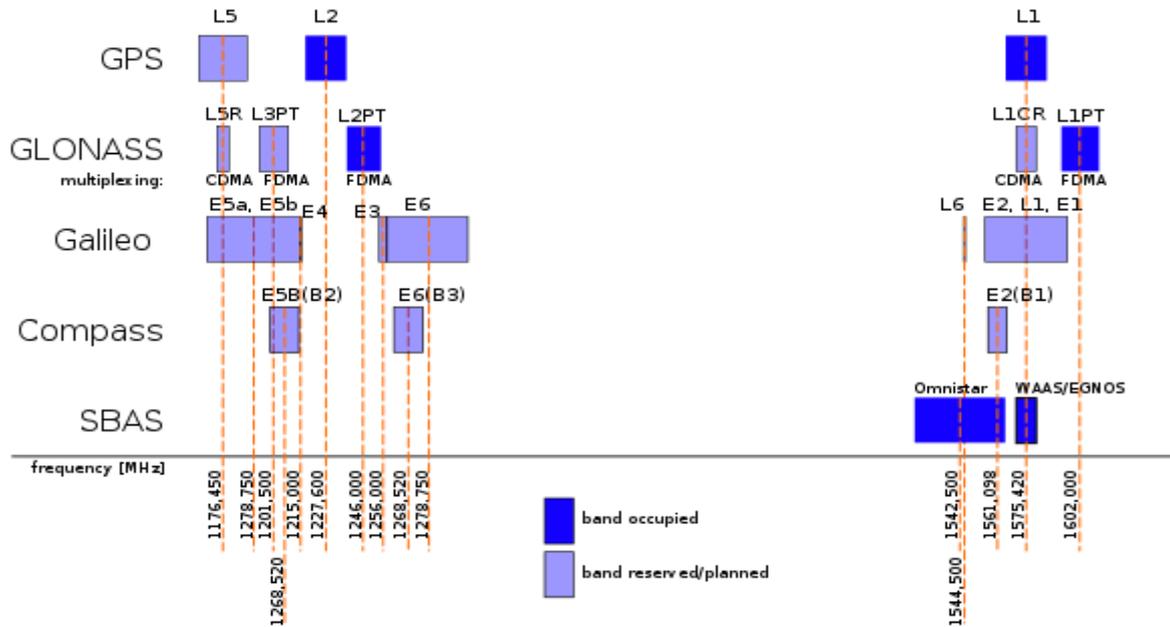


Fig. 6-14 Signal bands of the different current and future satellite systems.

From: Enemy - eigenes Werk, gemeinfrei, <https://commons.wikimedia.org/w/index.php?curid=4240670>

6.5.3 Summary: The Role of Water Vapor in the Atmosphere

During the chapter "Atmosphere" we have learned a lot about energy transformation and the structure of the atmosphere, about pressure and clouds and the radiation passing the atmosphere. Water vapor was mostly often not in the focus, even though it was present all the time. Thus, this paragraph aims to sum up the findings of the preceding paragraph with a special focus on the water (vapor).

- Water vapor is the most important natural **greenhouse gas**, since it absorbs IR radiation in a very broad range. Thus, a high amount of water vapor in the atmosphere is capable of heating up the atmosphere.
- If the atmosphere heats up, the **ice shields** will melt, and the **oceans** will evaporate water. During this phase change, the water "stores" (heat-)energy.
- **Snow- and ice-covered** regions reflect radiation back to space (albedo).
- When **clouds** are formed, the stored energy is set free again and heats up the atmosphere.
- The **formation of clouds** is dependent on the relative humidity, the pressure, the temperature as well as on the presence of aerosols.
- **Clouds have different effect** on the heat management of the earth. They can reflect IR-radiation back to earth, consequently heating it up or they reflect solar radiation back thus preventing the earth from heating up. The effect is also strongly dependent on the type of clouds, which, in turn, is dependent on the amount of water vapor and aerosols in the atmosphere.

7 GNSS and Smartphone

7.1 GNSS Measurements on your smartphone

The accuracy of smartphone positioning is usually in the order of a few meters whereas the professional antenna (e.g. TAI1, TAF1, TAD3) achieve an accuracy of a few centimetres to millimetres.



For the today's activity, you need to install the following application on your phone (Android): **GPSTest**.

<https://github.com/barbeau/gptest/wiki> .

It is an open-source and ad-free application. Here is also a QR-Code to the link.

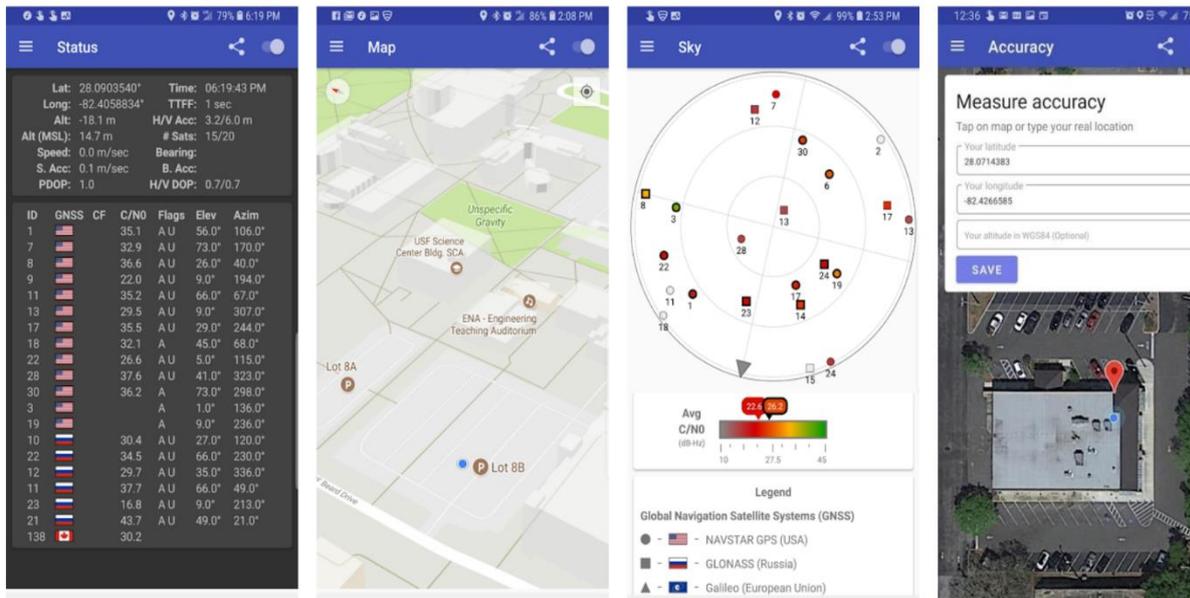


Fig. 7-1 GPSTest in use (screenshots)

The measurements/screenshots on the next page have been made with two other Android apps (Physics toolbox suite and GPS Status)

Exercises:

- a) Find out in which German town I have been recently!?
- b) The signal of how many Russian, Chinese and US satellites did I receive?!
- c) Does your cell phone capture satellites from other countries?!



GPS

Breitengrad: 50,0884950° Geschwindigkeit: ...
 Längengrad: 8,2517549° TTI
 Höhe: 215,0 m Genauigkeit: ...
 Alt (MSL): 167,3 m Bearb:
 Satelliten: 24/24

ID	GNSS	C/N0	Elev	Azim
12	USA	37.0	84.0°	337.0°
13	RUS	25.0	69.0°	341.0°
26	CHN	31.0	68.0°	297.0°
24	USA	41.0	54.0°	135.0°
25	USA	34.0	50.0°	263.0°
22	RUS	31.0	49.0°	64.0°
29	CHN	35.0	49.0°	79.0°
23	RUS	37.0	36.0°	150.0°
32	USA	31.0	35.0°	298.0°
13	CHN	27.0	34.0°	71.0°
12	RUS	32.0	33.0°	91.0°
8	CHN	18.0	28.0°	46.0°
19	USA	18.0	28.0°	47.0°
4	RUS	28.0	28.0°	303.0°
14	USA	27.0	24.0°	315.0°
6	USA	37.0	22.0°	82.0°
2	USA	30.0	19.0°	117.0°
3	RUS	40.0	19.0°	245.0°
24	CHN	33.0	17.0°	292.0°

- d) Go to the window of your classroom or to the courtyard and make a measurement with GPSTest. Take two screenshots like the above example and compare.
- e) On the following day go to our Database tryat.eu and compare your own mobile phone measurement with the one of a professional GNSS antenna.
- f) Draw the trace of one satellite in the sky for several hours with the aid of polar coordinate paper.

Nota bene: You have to choose the antenna which is closest to your school. The time specification of the TRYAT database is UTC not your local time!

Example: The Cell-Phone Measurement has been taken close to antenna TAD2 on August 5, 2019. The coordinates of the antenna are 52,430°N and 13,475°E.

The time was 11:22 local time. In UTC this is 9:22! We follow the GPS-Navstar satellite Nr. 21 which is close to zenith at that time. (The Tryat-database so far has only GPS satellite data)

Elevation (ϵ) = altitude of the satellite above the horizon.

Azimuth (φ) = the azimuth is an angular measurement in a spherical coordinate system with a reference vector pointing to true north.

Slants zeitabhängig

[Liesmich](#)

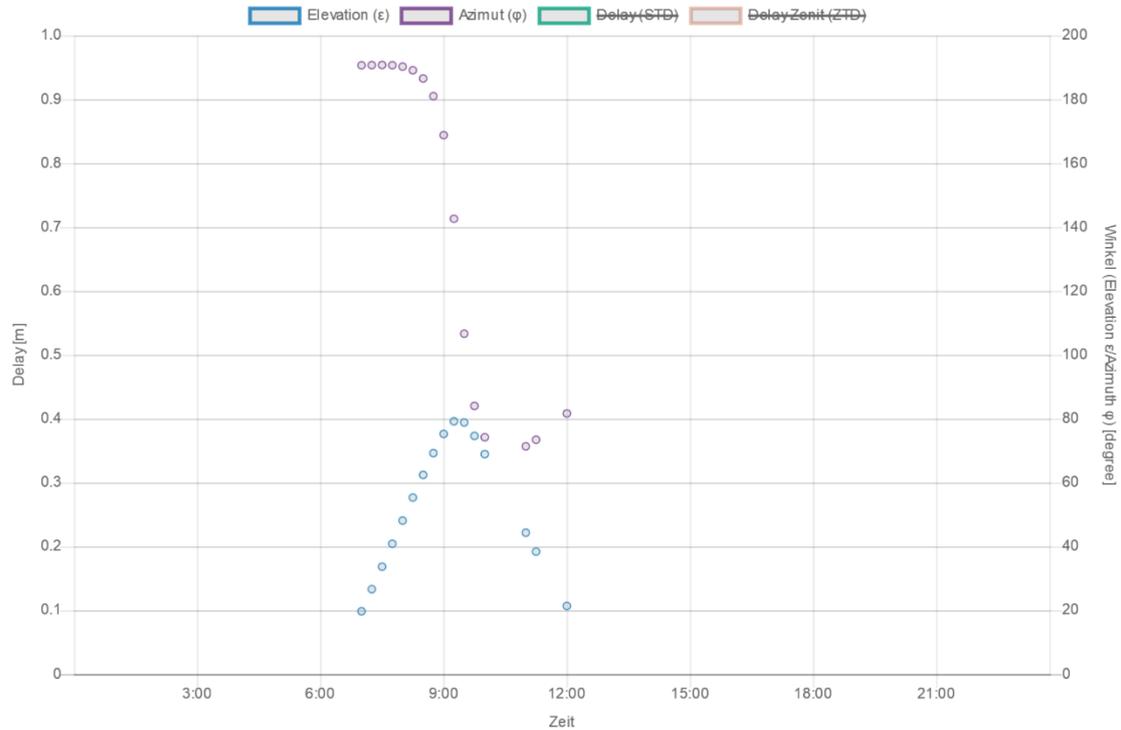
Alle Stationen

Station: TAD2 x=3789900 y=908119 z=5032220; l=13.4749 b=52.4303 h=105.102

Zeitraum: 2019-08-05 00:00:00 bis 2019-08-05 23:59:59

Satelliten: G21

Station wählen, Zeit einstellen und Satelliten wählen.

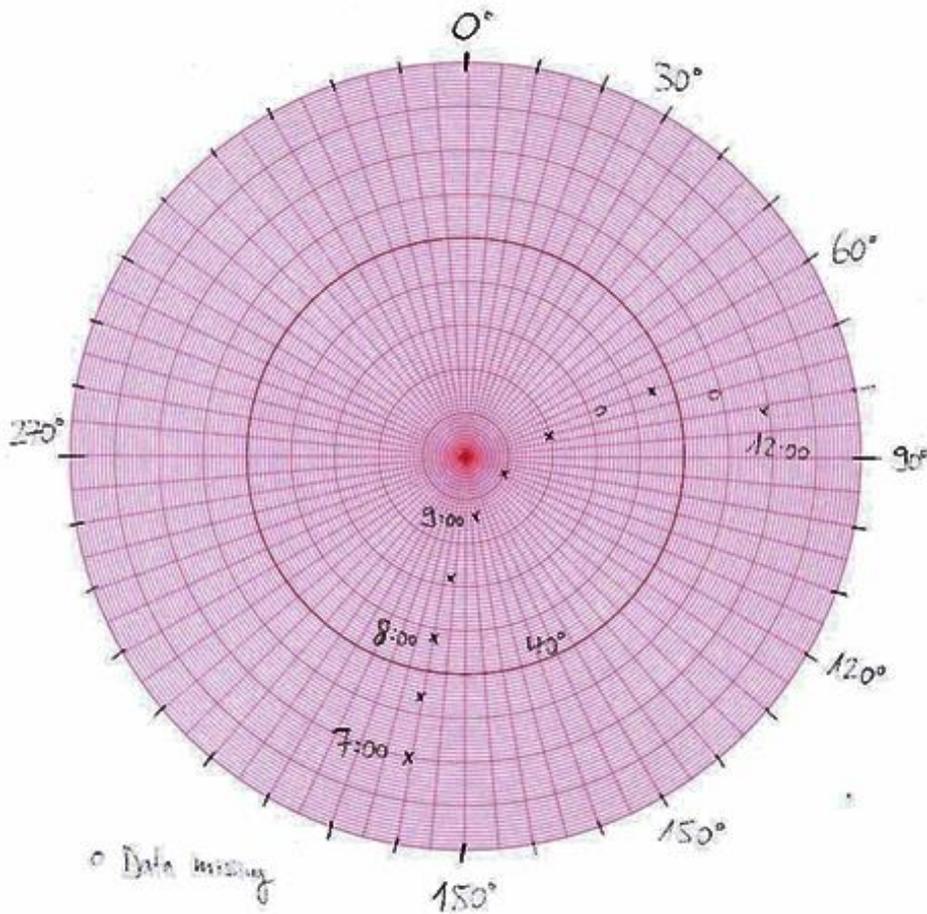


Tryat - Plots von Christian Hoffmann ist lizenziert unter einer [Creative Commons Namensnennung 4.0 International Lizenz](#).

UTC	eps/°	phi/°
07:00	20	191
07:30	34	191
08:00	48	190
08:30	62	187
09:00	75	169
09:30	79	107
10:00	69	74
10:30	*	*
11:00	44	71
11:30	*	*
12:00	21	82

* Data missing

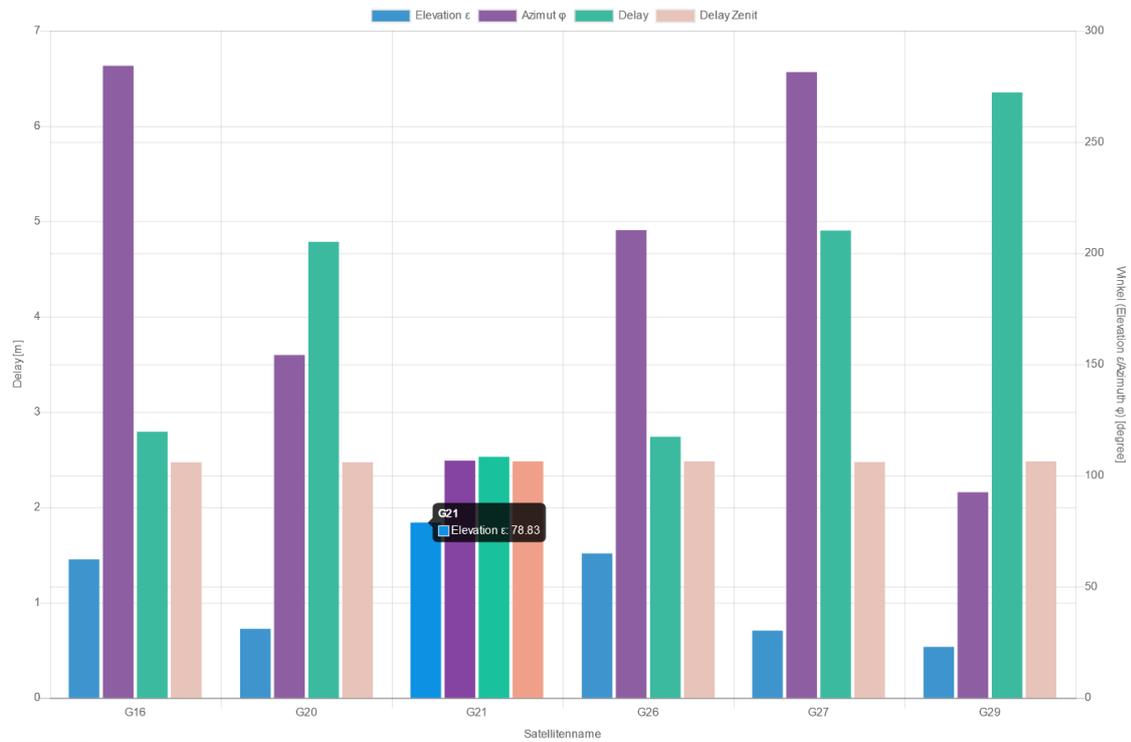




Station x=3789900 y=908119 z=5032220; l=13.4749 b=52.4303 h=105.102

Zeitpunkt 2019-08-05 09:30:19

Alle Satelliten



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8 Satellites Orbits

8.1 The Kepler-Problem: Five examples of Earth Satellites

These are simple problems to study in an undergraduate physics course with an interesting background: What types of satellites do we have around the earth and what is the use of them to each and every one of us?

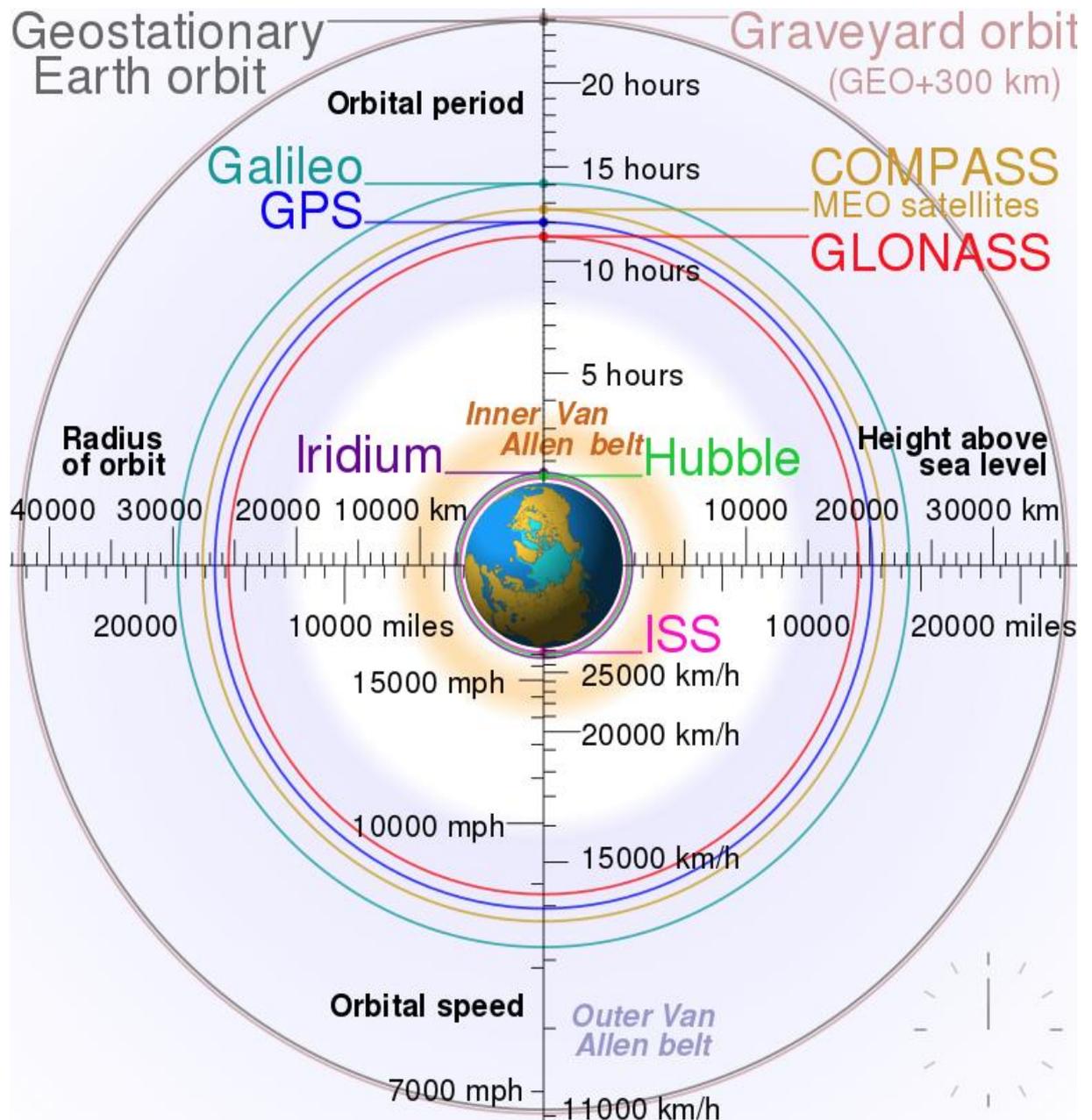


Fig 8-1 Comparison of different satellite orbits. By Cmglee, Geo Swan - Own work, Earth bitmap is File:North_pole_february_ice-pack_1978-2002.png by Geo Swan., CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=16891766>



Choose one of the following examples and recall Newton's law of universal gravitation and the three laws of Kepler and how you can derive them.

You can also visualize the satellite orbit as seen from earth with the following desktop program GPREDICT (gpredict-win32-2.2.1, freeware): choose your own location (e.g. Berlin) and a number of interesting satellites (e.g. ISS, Metop-C, GPS). Download under <http://gpredict.oz9aec.net/>

8.1.1 Weather satellites

- a) Explain exactly: How can a weather satellite orbit 800 km above ground (in a circular orbit)?
- b) Calculate the orbital velocity and compare with an object that is orbiting at zero altitude.
- c) Calculate the orbital period [T = 101 min]
- d) Calculate the number of orbits per day
- e) Analyse: What happens if the velocity of the satellite is increased by a 20%? How could the satellite be forced to leave the earth gravitational field?
- f) Prepare a short presentation for your class about weather satellites.

Some useful data:

Earth radius	$r_E = 6370 \text{ km}$
Gravitational constant	$\gamma = 6,67 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
Earth mass	$m_E = 5,98 \cdot 10^{24} \text{ kg}$
Orbital speed at Earth's surface	$v_{0,Earth} = 7,9 \text{ km} \cdot \text{s}^{-1}$
Escape velocity	$v_{e,Earth} = 11,2 \text{ km} \cdot \text{s}^{-1}$

8.1.2 Rosat - a X-ray satellite and its end

- a) Read carefully the following internet Link from DLR (German Aerospace Center) about ROSAT. https://www.dlr.de/content/en/downloads/news-archive/2011/20111025_rosat-re-entered-atmosphere-over-bay-of-bengal_1779.pdf?_blob=publicationFile&v=8
- b) Find out ROSAT's average height above the surface of the earth and calculate the orbital velocity and period (assuming a nearby circular orbit).
- c) Assume that ROSAT would fall from this height directly on earth without air resistance. Calculate by means of energy conservation the velocity and impact energy when reaching the ground.
- d) Prepare a short presentation for your class about the ROSAT Mission. What were its objectives and achievements?





Fig 8-2 : DLR, https://www.dlr.de/dlr/desktopdefault.aspx/tabid-10081/151_read-1779/#/gallery/3578

8.1.3 Geostationary satellite

- Illustrate the meaning of Newton's law of Gravitation. Sketch the gravitational field of a spherical mass.
- Show that a geostationary satellite can orbit (without having its own propulsion system) above a specific point on earth. Calculate (by means of the orbit time) the height of the orbit (above ground).
- Prepare a short presentation for your class about geostationary satellites. What are the typical applications? Choose one and explain even more detailed. Explain why in Europe Antennas for satellite TV are orientated towards south.

8.1.4 Galileo - a Global Navigation Satellite System (GNSS)

The Galileo Project of the European Union is mainly designated for civil navigation and time reference. It is an alternative and complement to the corresponding GNSS of USA (GPS Navstar), Russia (GLONASS) and China (Beidou). Until 2018 there have been 26 Galileo satellites brought up to space.

- The radius of the Galileo orbit is 23260 km. Calculate the orbit period and velocity.
- The GNSS satellites are sending their signal with a microwave frequency (L Band) of about 1,2 GHz. Calculate the corresponding wavelength and the period of time that the signal needs to travel down to earth.
- Prepare a presentation for your class about GNSS in general and more specifically the Galileo program.
- You can receive the GNSS signal with your smartphone. Check out with the application GPSTest (also recommended Physics Toolbox Suite, GPS Status; all Android). Compare with the result of the GPREDICT program.

8.1.5 The Japanese QZSS - a regional GNSS complement system

The Japanese Quasi-Zenith Satellite System (QZSS) has four operational satellites in a geosynchronous, slightly elliptical orbit. The orbit has an inclination of about 43° (geostationary would be 0°). The QZSS helps to improve the reception of GNSS signals especially in Japanese big cities ("urban canyons") and mountain regions. In fact, it is designed to ensure that one satellite is always almost directly overhead (elevation 60° or more) over Japan.

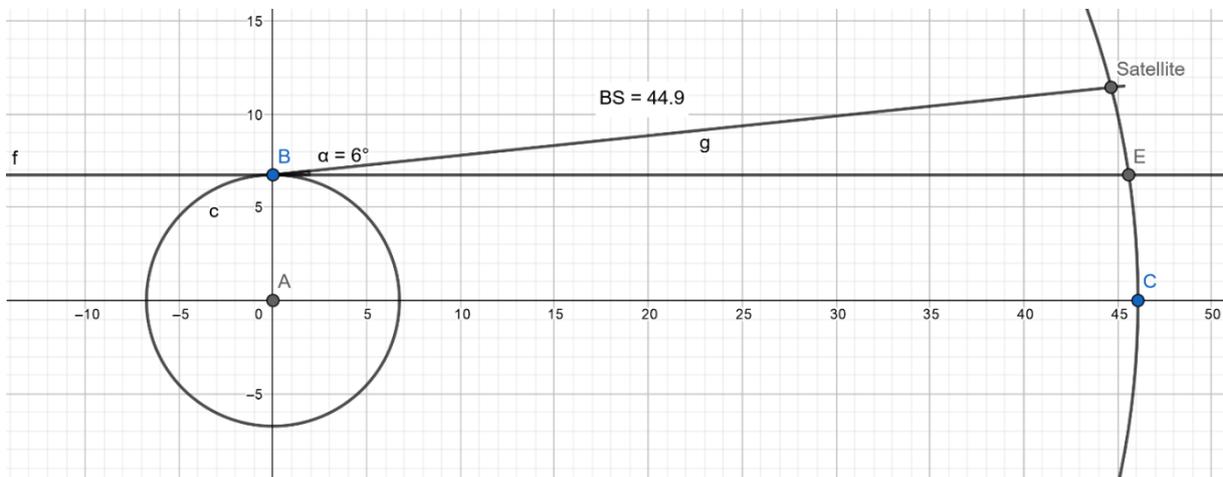
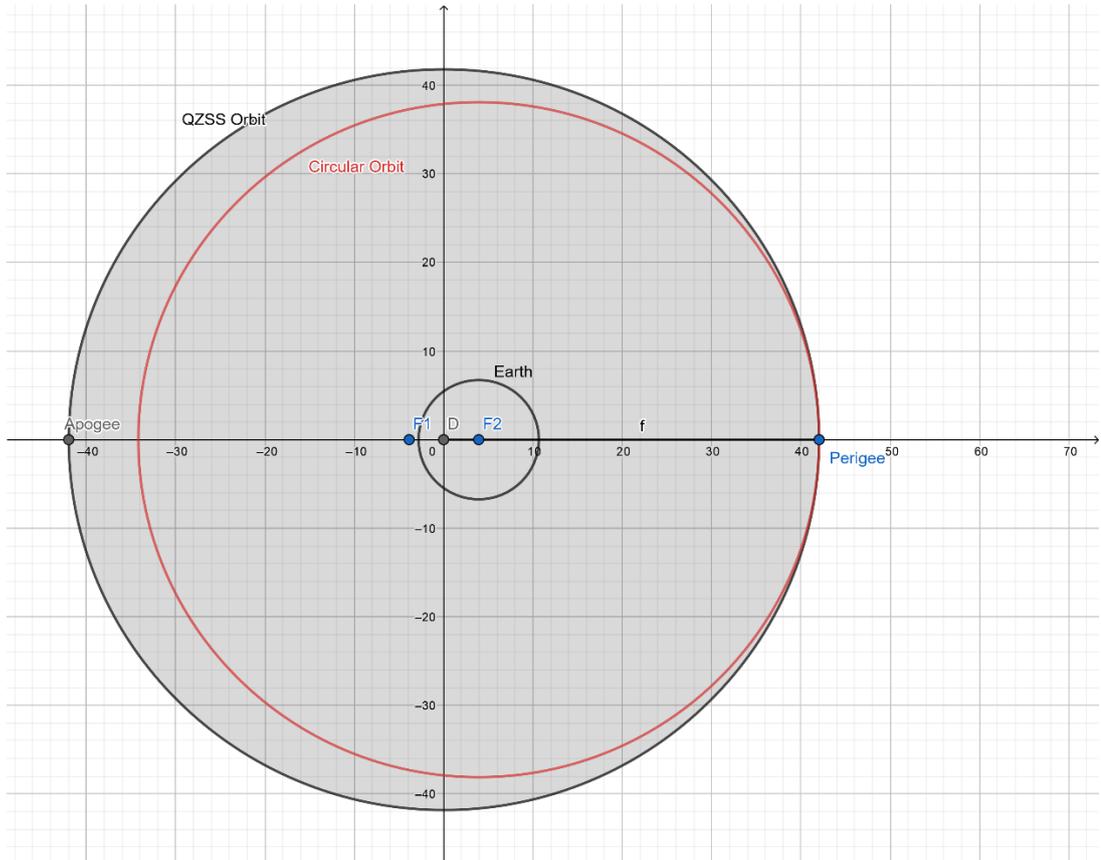
- The period of the geosynchronous orbit is 24 h. Calculate by means of Kepler's Third Law the length of the semimajor axis a .
- The numeric eccentricity of the orbit is $\epsilon = 0,075$. Calculate the linear eccentricity e . [$e = 3800$ km]
- Calculate the shortest distance to the earth center ("perigee") and the lowest altitude over earth ground.
- Use Geogebra (<https://www.geogebra.org/>) to draw the elliptical orbit with the Earth in one of the Foci.
- QZSS signal can also be captured from northern Europe with a very low elevation (cf. smartphone screen shot taken close to Berlin at March 22, 2019). Make a to-scale drawing of the receiver's position with a tangential plane and the QZSS satellite in the apogee.
- Prepare a short presentation for your class about the QZSS.



The screenshot shows a GPS application interface. At the top, it displays 'GPS' and status icons for signal strength, battery (23%), and time (18:07). Below this, location data is shown: Breitengrad: 52,3986008°, Längengrad: 13,3125312°, Höhe: 100,6 m, Alt (MSL): 57,4 m, and Satelliten: 20/20. To the right of this data are labels for 'Geschwindigkeit', 'TTI', 'Genauigkeit', and 'Bearir'. A table below lists satellite data with columns for ID, GNSS (with flag icons), C/N0, Elev, and Azim. A red '+' button is visible on the right side of the table.

ID	GNSS	C/N0	Elev	Azim
20		28.0	72.0°	249.0°
26		30.0	54.0°	223.0°
21		35.0	47.0°	187.0°
26		34.0	45.0°	297.0°
31		38.0	43.0°	233.0°
9		39.0	41.0°	171.0°
24		22.0	39.0°	301.0°
29		39.0	37.0°	66.0°
25		36.0	32.0°	131.0°
12		23.0	32.0°	243.0°
11		34.0	25.0°	324.0°
5		42.0	22.0°	63.0°
5		33.0	19.0°	127.0°
21		23.0	16.0°	234.0°
16		27.0	16.0°	301.0°
20		44.0	13.0°	72.0°
2		18.0	8.0°	349.0°
193		18.0	6.0°	47.0°
2		18.0	6.0°	42.0°

8.1.6 Solution



Some results for control.

No.	name	description	T	T in s	r (or a) in m	R in m (over earth)	Kepler constant R^3/T^2 in m^3/s^2
1	Weather Satellite (Example)	101min	6,09E+03	7,17E+06	8,00E+05	9,95E+12	1,01E+13
2	Geostationary Satellite	24h	8,64E+04	4,22E+07	3,58E+07	1,01E+13	1,02E+13
3	Rosat	X-ray satellite	96,25 min	5,76E+03	6,96E+06	5,85E+05	1,01E+13
4	Galileo	GNSS	14h	5,07E+04	2,96E+07	2,32E+07	1,01E+13
5	QZSS (Japan.)	geosynchron.	24h	8,64E+04	4,22E+07	3,26E+07	1,00E+13

9 Model experiment

9.1 Measurement of the height of a layer of water with the laser rangefinder

9.1.1 Preliminary test

Measure a length with a ruler on a transparent plastic cuboid. Repeat the measurement with a laser rangefinder, directing the beam through the plastic cuboid. Compare both values.

9.1.2 Interpretation of the deviation:

The laser rangefinder indicates a "false" result since it calculates the length from the relationship $L = c \cdot t$ and uses the value for air (c. $2.99 \cdot 10^8 \text{m/s}$) for the speed of light c . In the plastic cuboid, however, the speed of light is reduced by the factor n_K (refractive index of the plastic). Therefore, the "optical path length" is increased.

9.1.3 Model experiment for the determination of the content of water vapor in the atmosphere of Earth

On the left side, the determination of the water vapor content from GNSS data is shown schematically; on the right there is a model experiment to explain the principle.

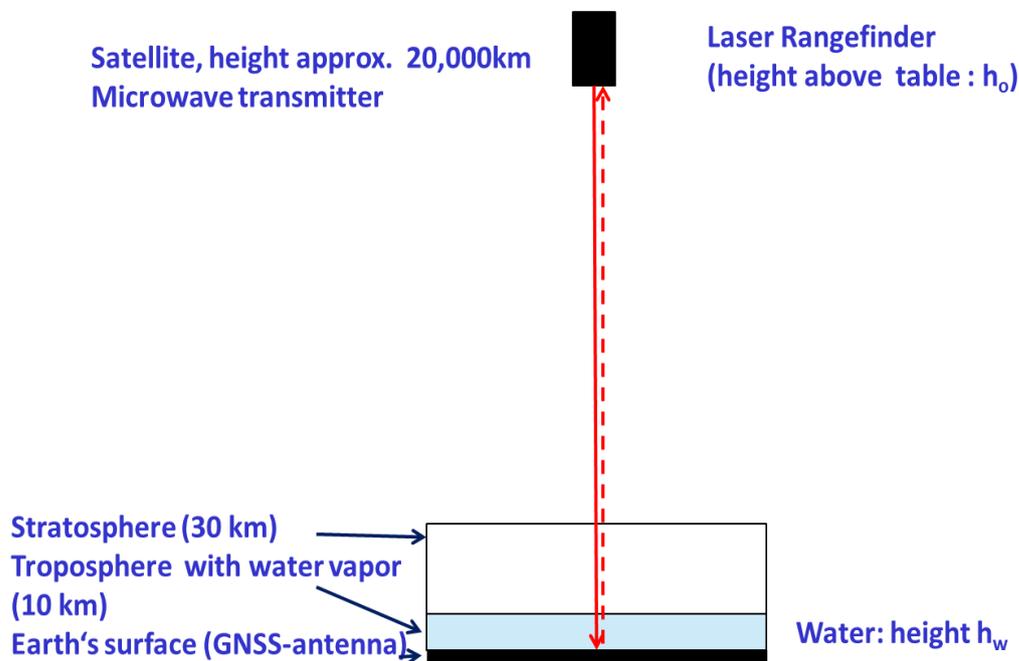


Fig 9-1 model experiment (TRYAT, CC BY-SA 3.0)

Differences between GNSS measurements and the model experiment:

- GNSS measurements are carried out with microwaves,
- in GNSS measurements, the receiver is an antenna on the ground, the signal is not reflected,
- the data from several satellites, generally not in zenith, is evaluated,
- the influence of water vapor in the earth's atmosphere on the optical path length is measured and then the water vapor content can be calculated using meteorological data (pressure and temperature).

10 Calculation of water vapor

Calculation of the atmospheric water vapor content from global navigation satellite system (GNSS) data

The speed of an electromagnetic wave is affected by the medium through which the wave travels. Depending on the density and the composition of the medium, the speed of propagation is reduced when compared to the vacuum. As a result, the propagation time of the wave is extended for a given distance. Alternatively, the extension of the transit time can be specified as an apparent path delay. The determination of the position via GNSS satellites, which are located approx. 20.000 km above the earth's surface, deviates several meters with respect to the propagation time in vacuum. For a very accurate position determination this must be taken into account, conversely, the measurement of the path delay allows the calculation of the water vapor content of the earth's atmosphere. This point will be worked on below.

10.1 Determination of the path delay in the zenith from GNSS data

10.1.1 Task

Go to the website <https://www.tryat.eu/stations-and-data/> PANEL E, slants delays, choose a dataset for a station, e.g. Potsdam POTS, Berlin TAD1, Pau TAF1, Naples TAI1

Note: Due to a time delay in data display (depending on the GNSS) the website displays older data. Hence you might choose to use data of the last week.

Explanation:

Elevation (ϵ) = Altitude of the satellite above the horizon.

Azimuth (φ) = an azimuth is an angular measurement in a spherical coordinate system with a reference vector pointing to true north.

Delay = Path extension of the signal in the direction of the satellite. (STD, Slant Total Delay)

Delay Zenith: Converted path extension for the zenith direction. (ZTD, Zenith Total Delay)

Get the Zenith Total Delay (ZTD) for a certain time:

Station: Date: Satellite: Time:

ZTD:

10.2 Calculation of the water vapor content

The zenith total delay (ZTD) can be split into a hydrostatic delay (ZHD) and a wet delay (ZWD). The dry fraction is determined by the air pressure, the moist fraction by the water vapor content. The following equation applies:

$$ZTD = ZHD + ZWD$$

For meteorology and climate research the wet part, ZWD, is of interest. The dry part can be calculated with known total pressure after a model. Then follows:

$$ZWD = ZTD - ZHD$$

and

$$ZHD \approx 2.277 \cdot 10^{-3} \frac{\text{m}}{\text{hPa}} p_0$$

10.2.1 Tasks

1. Look for the air pressure for the same location and time from the Troposphere Data on PANEL D of the website.

$p_0 =$

2. Calculate the dry fraction and then the wet fraction using the equations given above.

ZWD:

In meteorology the water vapor is given in mm water column -> Precipitable Water Vapor (PWV). Here is the simple proportionality: $PWV \approx 0.152 \cdot ZWD$

3. Calculate PWV with your data and compare the value with the value given in PANEL D or in the weather table (PANEL F).

Calculated PWV:

PWV from PANEL F:

10.2.2 Example

Record: Station POTS, 01.05.2019, 12:00:19, Satellite G25

Elevation (ϵ) = 73.77° , Delay (STD) = 2.4759 m, Delay Zenith (ZTD) = 2.3774 m

$ZTD \approx STD * \sin(\epsilon) = 2.772$

PWV (PANEL D) = 16mm, $p_0 = 1000.5$ hPa

$ZHD = 2.277 * 10^{-3} \text{m} / \text{hPa} * 1000.5 \text{hPa} = 2.2781$ m

$ZWD = ZTD - ZHD = 2.3774 - 2.2781$ m = 0.09626 m

$PWV = 0.152 * ZWD = 0.152 * 0.09626$ m = 0.015088m = 15.1 mm

Deviation: 0.9mm

(Note: The calculation is done for data of a specific satellite; the values in PANEL D are mean values for the station.)

10.2.3 Further tasks

- Describe the path that the satellite takes through the sky (PANEL B and C).
- Compare Slant Delay and Zenith Delay and explain the differences (PANEL C).
- Try using simple trigonometric functions to calculate the zenith delay from the delay and the elevation angle.

10.2.4 Further possible examination examples

- - Change of water vapor during one day
- - Difference between a summer and a winter day
- - Compare data in Pau, Berlin, Naples for the same point in time.

Lit: Ming Shangguan, Analysis and derivation of the spatial and temporal distribution of watervapor from GNSS observations, PH-D-Thesis, TU-Berlin, 2014.

10.3 Example: Thunderstorm

The following picture (fig 10.1 shows the changes of water vapor during two heavy thunderstorms observed near Potsdam on the 11th and 12th of June 2019. On the 11th, the water vapor increases between 5 pm and 8 pm (UTC) from 30mm to 42mm, after 8 pm follows a decrease to 28mm at midnight. Lightning happens when there exists a big, fat cloud with positively and negatively charged particles to its top and bottom, respectively. At the time between 8:30 pm - 9:00 pm (UTC) there had been a cloud to cause the lighting, this means the water vapor (partly) condensed to form that cloud and hence its amount was reduced. The changes of water vapor with the increase and decrease agree with the time of the lightning and the time of the thunderstorm¹⁾. A similar behavior is observed on the next day between 2 pm and 8 pm: a strong increase of the water vapor in the troposphere just before a Thunderstorm. Therefore monitoring the water vapor should be useful for the prediction of thunderstorms.

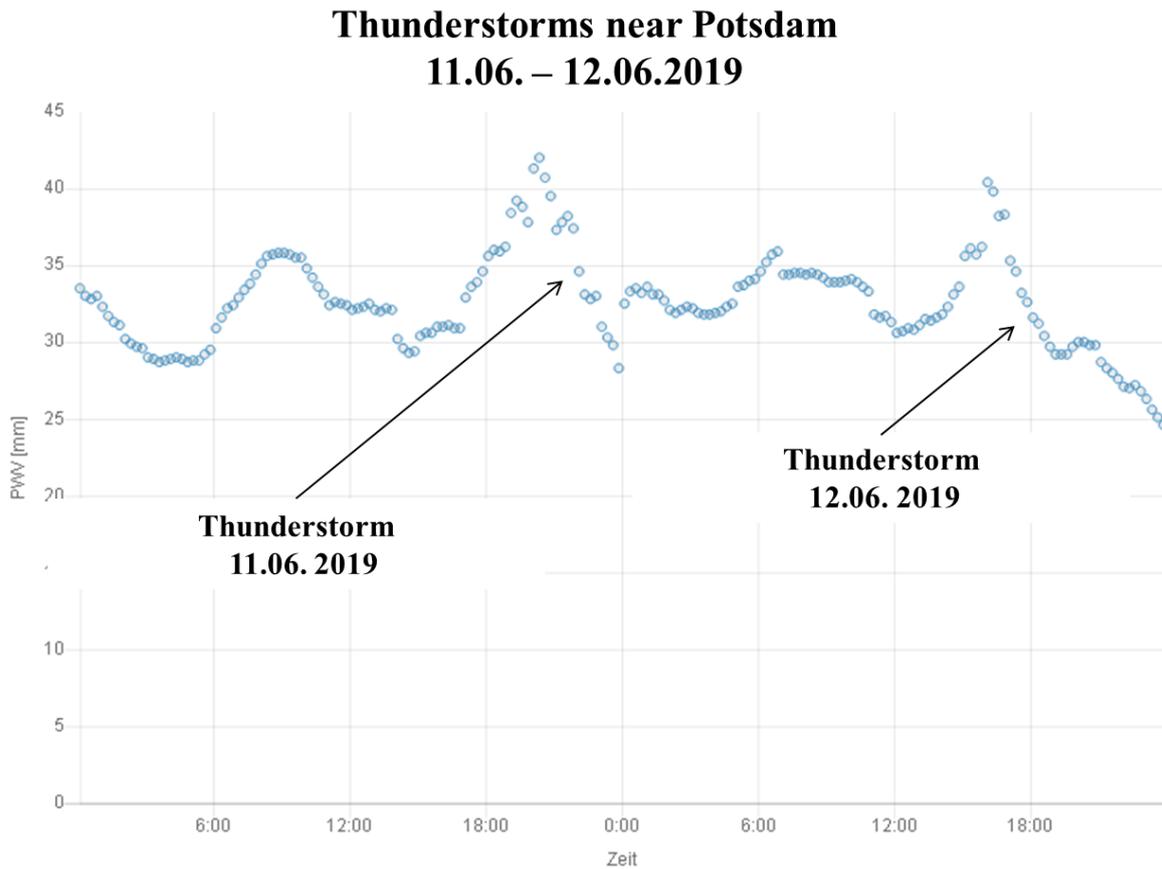


Fig. 10-1 Precipitable Water Vapor (PWV) during Thunderstorms at station POTS

¹⁾ <https://kachelmannwetter.com/de/blitze>