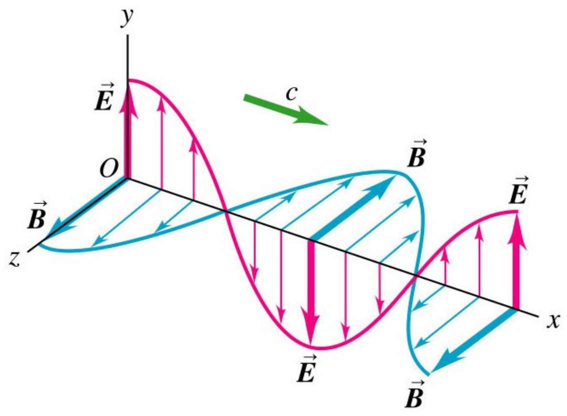
Chapter 3. Electromagnetic Waves & Electronic devices

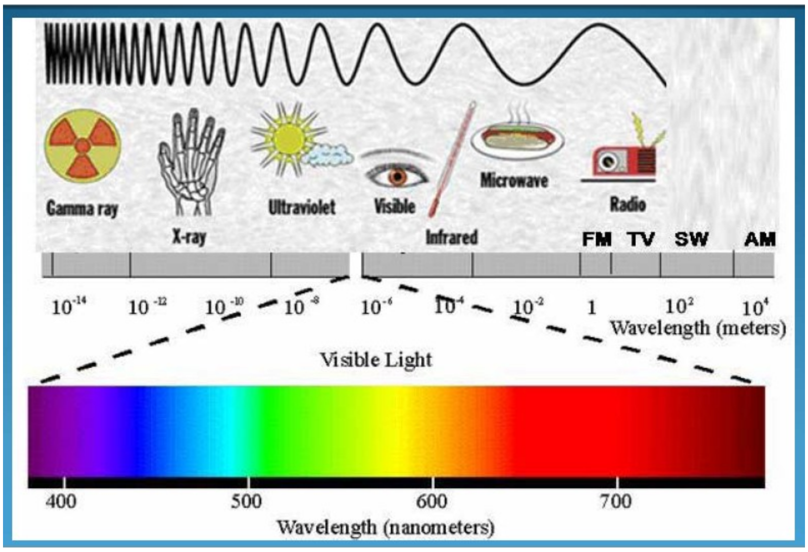
3 Electromagnetic Waves

The electromagnetic field vectors normally describing the electromagnetic waves are the electric field and magnetic field vectors.



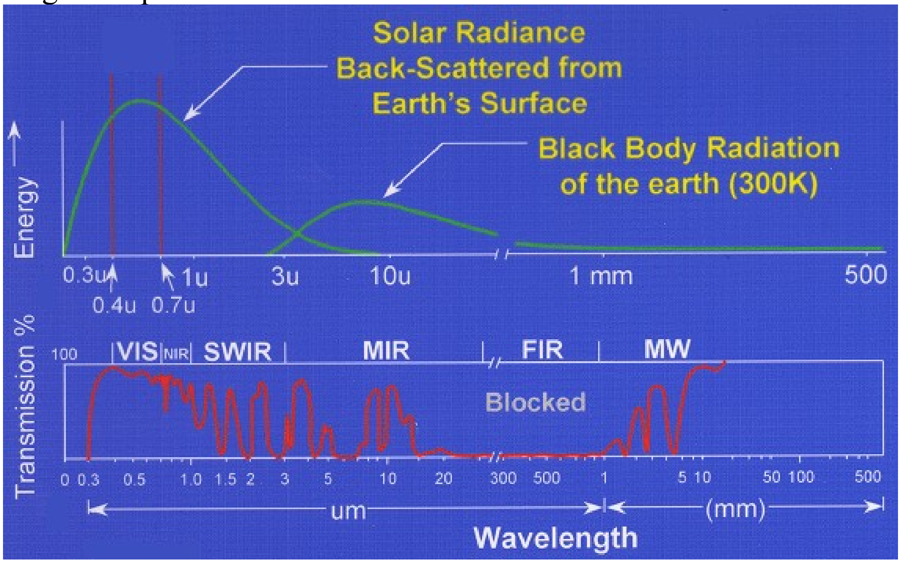
Above is shown how an electromagnetic wave moves far away from an antenna where it is generated. One observes that the magnetic field (*B*) and the electric field (*E*) are completely in phase. Close to the antenna, the picture changes drastically, and the fields *B* and *E* are out of phase. When looking at light coming from a far object the waves are also called plane waves.

3.1 The Electromagnetic Spectrum



In the figure above we see the electromagnetic spectrum from the gamma ray-region around 10^{-14} m to the radio region up to a wavelength around 10 km. The visible wavelength region covers from the violet at 400 nm to 770 nm in the red. We use the expression $c = f\lambda$ to convert frequency to wavelength and vice versa.

When studying the interaction between the human body and radiation, one observes that radiation with high frequencies such as γ-rays the atoms cannot absorb these high energies, why most tissues are transparent. However, ionization can take place (Chapter 2). When reaching the ultraviolet region this radiation is strongly absorbed, already at the skin. High energy UV radiation can also ionize. The visible wavelength region has energies around 1-10 eV that corresponds to atomic transitions in the body why strong absorption occurs. When the light reaches the infrared region we experience this as heat, since these wavelengths sets the molecules in vibrational modes. At longer wavelengths in the millimetre region the human body is almost transparent. However, when the energy corresponds to water vapour absorption, the energy can also be absorbed by the human body (microwave ovens). The human body is transparent to Radio and TV waves. Below is also shown parts of the electromagnetic spectrum:



We observe that on the left part of the spectrum the atmosphere does not transmit waves below 0.3 µm or 300 nm. This is due to the absorption of ozone molecule, O_3, as well as of O_2 and N_2 in the atmosphere. Both O_2 and N_2 have absorption bands below 300 nm. We also observe that transmission of solar light is blocked between 15 µm and 1000 µm.

Ultraviolet wavelength regions

Looking at solar protection and protection from ultraviolet lamps regarding biological effects, one divides the ultra-violet wavelength region into three different areas: UVA (315-400 nm), UVB (280-315 nm) and UVC (100-280 nm):

UVA (315-400 nm):

The safety limit for UVA that has a thermal damage impact is set to 10 kJ/m^2 for a single occasion or to 10 W/m^2 when having a long time exposure. This radiation does not give suntan, but goes deeper into the skin and can result in more rapid aging of the skin. It causes damage to collagen and changes in the DNA can also result in cancer.

UVB (280-315 nm):
Exposure to UVB radiation will cause severe sunburn and some forms of skin cancer. One has found that UVB also causes damage to collagen but still at a very much slower rate than UVA radiation. The threshold dose from apoptosis to necrosis is 25 kJ/m^2. This corresponds to roughly 20 minutes of environmental UVB exposure.

UVC (100-280 nm):
The threshold for this low wavelength area is 30 J/m^2, which corresponds to around 10 minutes in a tropical area. One can compare this with standing around 0.5 m from an arc created by an electrical welding device. The damage is more of the photochemical type.

($\lambda < 200$ nm): Wavelengths below 200 nm belongs to the **extreme ultraviolet** region or **vacuum UV** (VUV) wavelength region. These wavelengths are absorbed in the atmosphere by molecular oxygen, O_2 and nitrogen, N_2. These wavelength areas are close to the X-ray region.

In a solarium UV-lamps with fused silica glass (”quartz”) transmit the UV-radiation. On the surface there is also a thin film layer cutting the UVC and parts of the UVB radiation, just transmitting the UVA radiation. This means that the damage of the skin is being reduced.

UV-INDEX

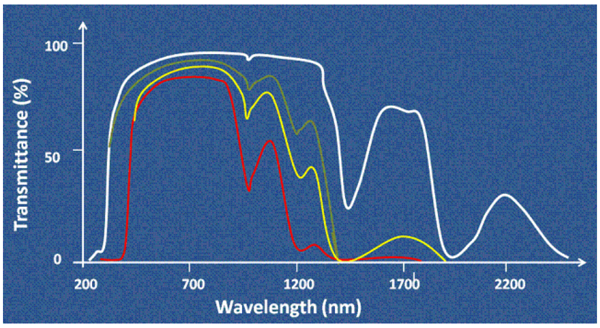
Depending on the position of the Sun above the horizon, the UV-radiation hitting the ground varies considerably. Of course clouds and rain reduce the intensity. When the radiation hits humans it is very dependent on the type of radiation, i.e. it is wavelength dependent (see above). A weighted result regarding the UV-influence on humans has been calculated. In 1994 *World Health Organization* (WHO, World health organization) made a World standard about the so called UV-index and how it should be presented all over the World.

The total biological effect of UVA and UVB radiation is collected as a UV dose rate and the unit for the dose rate is [mW/m^2]. It can be given as a so-called UV index. The scale is set to UV index =1 for 25mW/m^2 (weighted average of incoming UV radiation between 295 nm and 325 nm). In the North, the UV indices vary between 0–7 at sea level. In Equatorial regions or high altitudes it can reach 20.

The incoming UV-radiation is in Sweden measured by SSI, Statens Strålskyddsinstitut in cities as Stockholm, Visby and Halmstad. “Sveriges meteorologiska och hydrologiska institute”, SMHI, makes an UVI-prognosis based on the measurements during April to August.

UV Eye safety

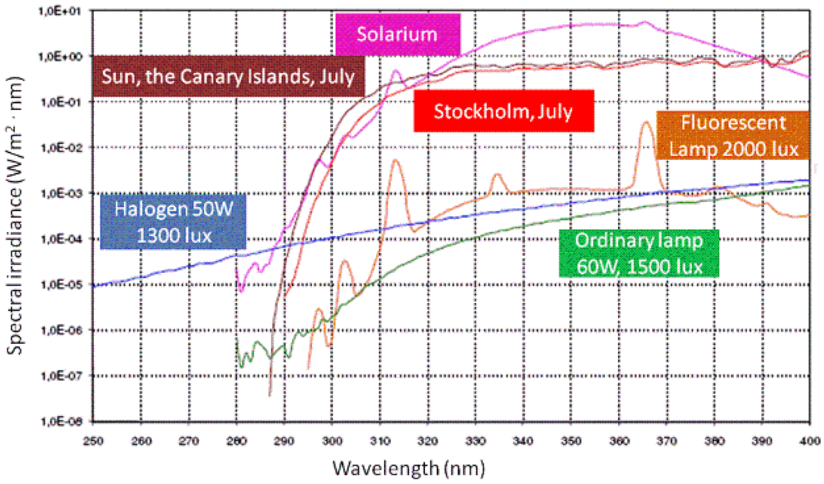
The eye globe can be exposed by UV radiation, both directly by light from the Sun, and as scattered radiation. Sun rays can hit the cornea from above and be focused by the eyes own optics why high intensities within the eye can be reached. The UV radiation hitting the eye is damped in the different parts of the eye depending on the wavelength as is shown below. However, absorption of some kind has to be achieved in order to obtain a biological effect.



Spectral transmission through the parts of the eye; from the cornea (outer part of the eye, white), through the **outer part of the lens**, through the **lens**, through the glass ball and to the **retina**.

All radiation with λ <290 nm is attenuated in the cornea, whereas radiation from 300 nm to 370 nm is completely attenuated in the lens. However, a small fraction around 320 nm reaches the retina. The transmission of UV and blue light is reduced with age. The eye transmits 90% of long-wave radiation up to 1 µm.

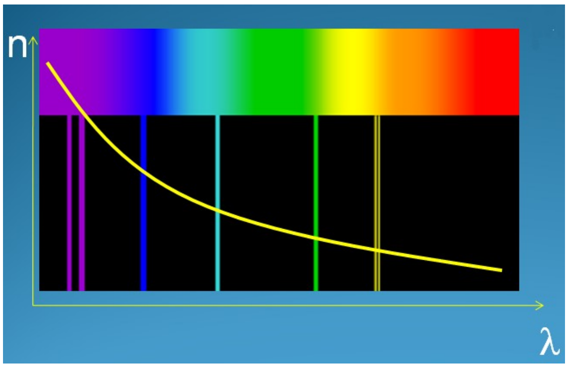
Below are shown the spectra obtained from different light sources, such as solarium lamps, the Sun, halogen lamps as well as ordinary tungsten lamps.



3.2 Plane waves. Speed of light

When looking at the

The speed of light in vacuum has the value $c = 2.99792458 \times 10^8$ m/s and is the so-called standard value in consistence with the meter definition. The speed is lower in all media and can be described by the refractive index n:



$$n = \frac{c}{v}$$

$$\lambda_0 = \frac{c}{f} = \frac{c}{v/\lambda} = \lambda \cdot \frac{c}{v} = \lambda \cdot n \Rightarrow$$

$$\lambda = \frac{\lambda_0}{n}$$

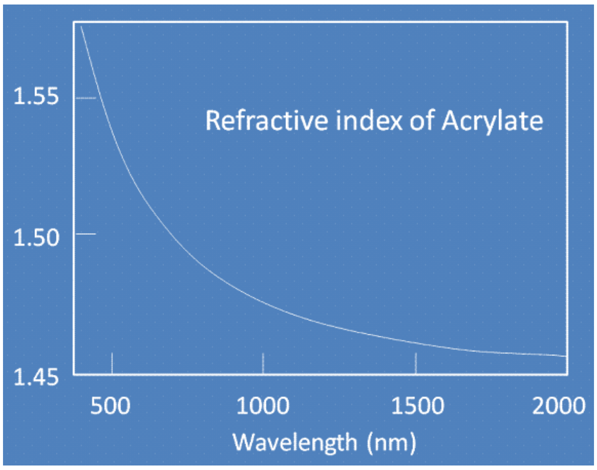
The refractive index is defined as $n = c/\upsilon$ where c is the speed of light in vacuum and υ is the velocity in a medium. Above is shown how we can get the wavelength in a medium when the refractive index is given. In the figure above we observe how the refractive index changes with wavelength. An experimental expression is given by:

$n = A + \frac{B}{\lambda^2}$ Here, A and B are materials constants.

In the literature, normally the refractive index is measured using the wavelength of the sodium atom, at λ = 589.3 nm;

Material	**Measured at the wavelength (nm)**	**Refractive index *n***
Vacuum		1 (exactly)
Various gases at 0ºC at 1 atm		
Air	589.3	1.000293
He	589.3	1.000046
H_2	589.3	1.000132
CO_2	589.3	1.00045
Various liquids at 20ºC		
Ethanol	589.3	1.361
Water	589.3	1.333
Silicon oil	589.3	1.520
Various crystals		
Diamond	589.3	2.42
Quartz (fused)	589.3	1.46
Glass (crown)	589.3	1.52-1.63

Below is shown how the refractive index changes with wavelength for an Acrylate film.



At 632.8 (He-Ne laser) nm the refractive index is 1.49.

3.3 Electromagnetic energy flow and power

When a plane electromagnetic wave passes through a volume it contains an energy that is connected to the electric and magnetic fields:

$$u = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

Since in a plane wave, there is a simple relation between the electric and magnetic field, i.e

$$B = \frac{E}{c}$$

If we use this expression we end up with the following energy per volume (J/m^3)

$$u = \varepsilon_0 E^2$$

When looking at the Sun, we can measure the energy flow that reaches the Earth and we find that S = 1.38 kW/m^2 is the intensity or in our case the solar constant. This is measured on a surface perpendicular to the incoming rays from the Sun. If we tilt this area A, we get the following area (effective area) we have to use, i.e.

$$A' = A\cos\theta$$

Where θ is the angle we tilt the area A.

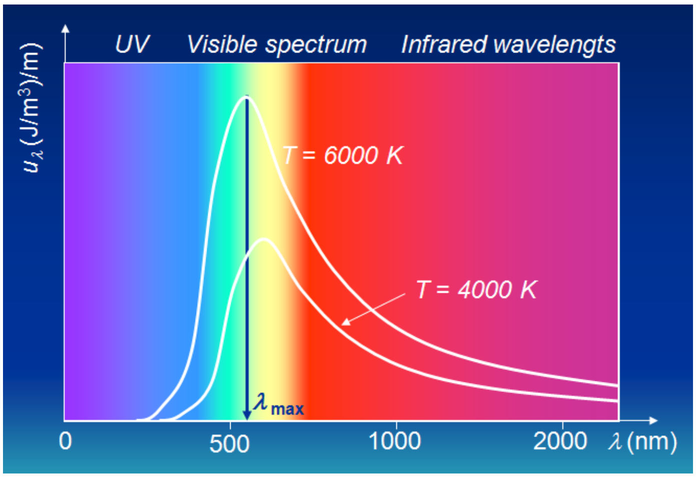
Let us introduce the Poynting vector that is said to carry the intensity of the wave:

$$\vec{S} = \frac{\vec{E} \times B}{\mu_0}$$ where the unit is W/m^2,

If both the electric field and the magnetic field can be expressed as cosine-waves and if they are in phase we get the mean value of the intensity as:

$$S_{mean} = \frac{E_0 B_0}{2\mu}$$ where the unit is W/m^2,

The incoming radiation from the Sun is shown by the Planck curve below:



The surface temperature of the Sun is around 6000 K and can be seen in the diagram, as well as a curve for a “cooler” body at 4000 K. We observe that most of the radiation is found in the infrared wavelength region. At 555 nm we have the maximum of the curve, where also the human eye has its highest sensitivity.

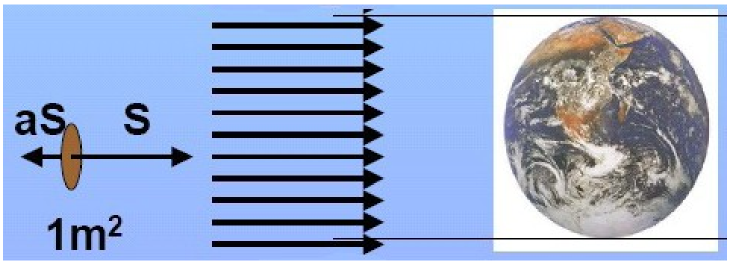
Besides the intensity unit we also have the Lumen definition and the Lux definition that stands for lumen per square meter. Both units are is related to human vision (See hyperphysics).

3.4 Intensity and solar cells. Solar energy. Solar energy parks

From the diagram (2005) below we see that so far, solar energy (solar heat, solar cells (photovoltaic)) only produces around 7% of the Worlds renewable energy:

🟪 **Large hydro 58.23%**	🟪 **Small hydro 5.12%**	🟨 **Wind power 4.58%**	🟦 **Biomass elec 3.42%**
🟦 **Geothermal elec 0.72%**	🟩 **Photovoltaic 0.42%**	🟥 **Other elec** 0.05%**	⬛ **Biomass heat* 17.08%**
🟦 **Solar heat 6.83%**	🟥 **Geothermal heat 2.17%**	🟦 **Biodiesel fuel 1.21%**	🟨 **Bioethanol fuel 0.16%**

The incoming light from the Sun results in a temperature *T* at the surface of the Earth.



and can be described by the following equation:

$$(1-a)\frac{S}{4} = \sigma T^4$$

The constant a stands for the so called *albedo* and has been measured by satellite observations to be $a = 0.30$, and S is the so called solar constant, $S = 1.38$ kW/m^2, the influx of radiation from the Sun. This results in a temperature of the Earth of T = 288K = -18ºC. However, the actual mean value of the temperature of the Earth is $\boldsymbol{T}$ **= 288 K = 15ºC**. This difference in temperature is caused by the Greenhouse effect (See Environmental Science I).

3.4.1 Solar Energy


Solar panels used for power production.

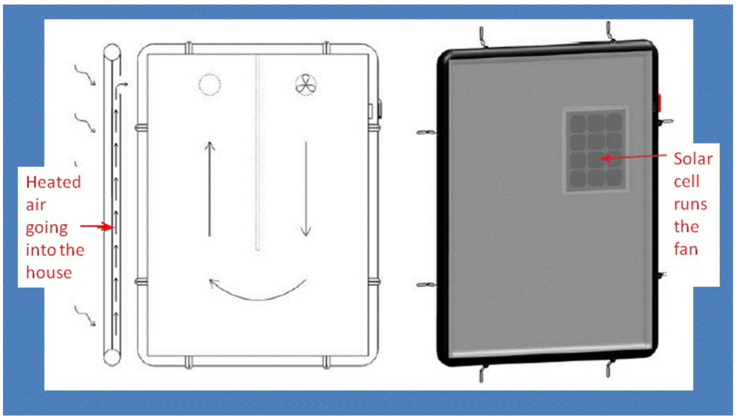

Solar tower onto which the sunlight is focused.

Introduction.

In this chapter we will discuss both the **solar absorber** and the **solar cells** based on the photovoltaic effect. The solar absorber is a rather simple device where the solar influx is directly converted into heat normally using water as a medium.

Solar absorbers

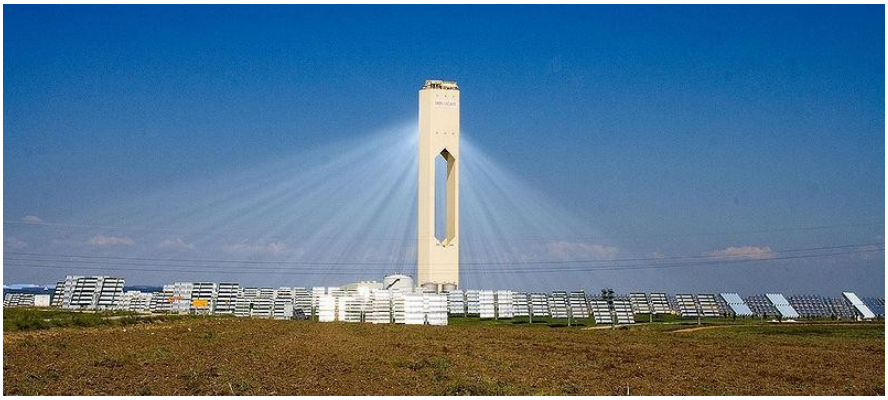
The incident power from the Sun has a mean Intensity of 1.38 kW/m^2, the *solar constant*. However, the *albedo* (the part of the incoming solar energy that is absorbed by the atmosphere) is 0.30, why the intensity that reaches Earth is a level of 0.97 kW/ m^2, or approximately 1 kW/m^2. At the ground level we can use this incoming light in several ways to gain energy.



A rather newly developed system for collecting solar energy is shown, where a transportable solar absorber with an area of 4.7 m^2 equipped with a solar cell (20W) connected to a fan that drives the heated air into the house. The air flow is around 200 m^3 per hour. The mean power is around 1200 W. This system is portable and can be used preferably in autumn, winter and spring in summer houses. The sun hits the absorbing canvas where the solar energy heats the air behind it that is pushed by a solar driven fan moving the heated air into the house (www.soltechenergy.com).

Solar power plants

A *solar reflector* can be used to produce energy via an absorbing medium. Using a parabolic mirror one can focus the solar light on the absorbent, normally a tube with circulating water. Near Sevilla in Andalusia in Spain the Worlds largest solar plant has been constructed to convert solar energy to usable power.



The picture shows the solar tower, where the parabolic mirrors on the ground are focused on.

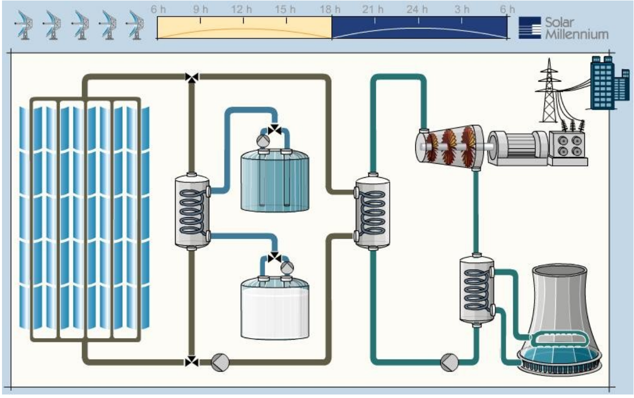
The solar park with the two towers receiving the sunlight from the large parabolic mirrors.
(by courtesy of Solar Millenium)

Example

Each parabolic mirror has an area of 14x6 m^2 and the large solar park to the left consists of 400 mirrors. How much power can we deliver to the tower?

Solution

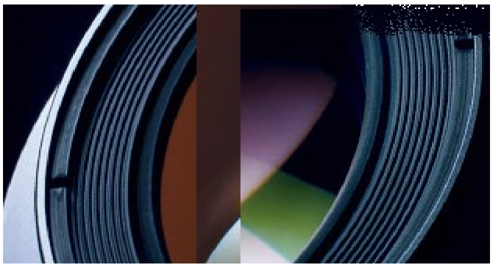
The solar constant is I = 1.38 kW/m^2. The albedo is 0.3 why we get $P = I \text{ x } A$ = (1-0.30)x 1.38x10^3 x 400x 14x6 W = 32 MW.



In the figure, the principle of operation can be seen. The sunlight is focused on water filled pipes with circulating water going to a heat exchanger and after some steps to a steam turbine for electricity production. The parabolic mirrors can turn, making the in-coming light always perpendicular to the sunlight.

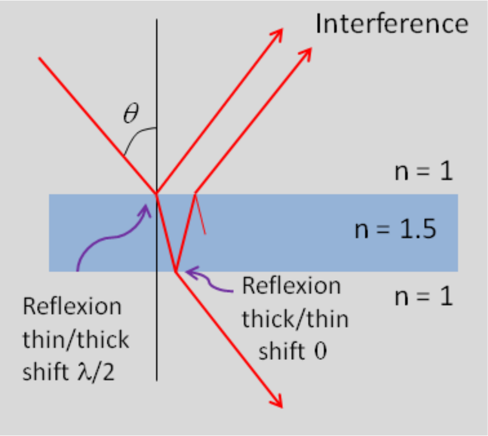
3.5 Interference. Thin films

When trying to avoid unwanted illumination, one often uses thin films to minimize the light.



Camera lenses consist of several internal lenses, where many surfaces are coated with thin films that minimize the internal reflections to prevent unwanted to reach the CCD at the focal plane. Both the front surface as well as the rear surface is coated as well as inner surfaces.

Let us look at the figure to below, where monochromatic light hits a surface at an angle θ. If we want to have a Maximum when the two rays interfere, they have to be in phase with each other. If we want a Minimum to occur, they have to shift $\lambda/2$ to be out of phase.
There are two details to take care of. Firstly the difference in pathways between the two rays that will interfere and one can show that the path difference will be:



$\delta = 2nd \cos\theta$

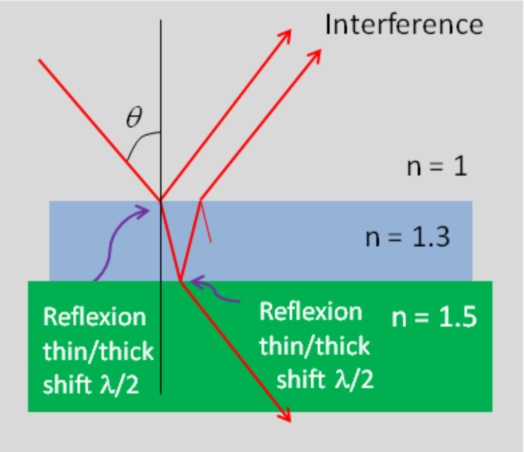
where n is the refractive index of the thin film. Secondly, we have to look at the reflexions as indicated in the figure. When reflexions take place where the light comes from a medium with lower refractive index than the medium it enters, there is a phase shift or a change in wavelength by $\lambda/2$ (thin/thick). Thus we have to add the effects to become the following:
Optical path difference + Phase difference = Condition of maximum or minimum.

$2nd \cos\theta + (\lambda/2 - 0) = (p + \frac{1}{2})\lambda$ for a **Minimum** to occur →
$2nd \cos\theta = p\lambda$ with $p = 0, 1, 2, \ldots$

Example
If we want to develop a thin film ($n = 1.41$) that makes the wavelength 513 nm to have its minimum in reflected light. Determine the thickness of the thinnest film. Set the angle to 0°.

Solution
If we use the figure above we get for a minimum: $2nd \cos\theta = p\lambda$, with $p = 0, 1, 2, \ldots$. In our case, where $\cos\theta = 1$, why $d = p\lambda/2n$. With $p = 1$ we get the thinnest film:
$d = \lambda/2n = 514/(2\text{x}1.41)$ nm = 182 nm = $181 \text{ x}10^{-9}$ m = 0.181 µm.

Interference in multiple layers



When one wants to avoid reflexes one can put a thin film (often MgF_2) on a piece of glass as is shown in the picture. If the light comes from air (n = 1) and enters a layer with n = 1.3 where the secondary reflections takes place between the materials with refractive indices 1.3 and 1.5. In these cases we have wavelength shift of the same kind, i.e. λ/2 in both cases, why the difference is (λ/2- λ/2) = 0. The following relation then holds if the thickness of the layer is *d*:

$2nd\cos\theta + (\lambda/2 - \lambda/2) = (p + ½)\,\lambda$ for a **Minimum** to occur →
$2nd\cos\theta = (p + ½)\,\lambda$ with $p = 0, 1, 2, \ldots$

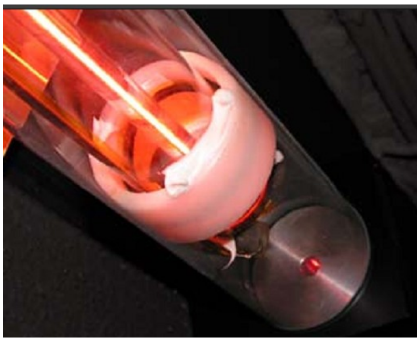
If the angle is 0°, the thinnest layer will have the thickness: $d = (0 + ½)\,\lambda/2n = \lambda/4n$
In this application with $n = 1.3$ and if we have laser light with $\lambda = 633$ nm we get
$d = 633/(4\text{x}1.3)$ nm = 121 nm = 0.12 µm.

3.6 Radiation damage by light. Avoiding radiation damage

Lasers can be hasardous. They can cause severe eye damages. Also reflexes from high intensity lasers are dangerous.

Laser light is monochromatic.

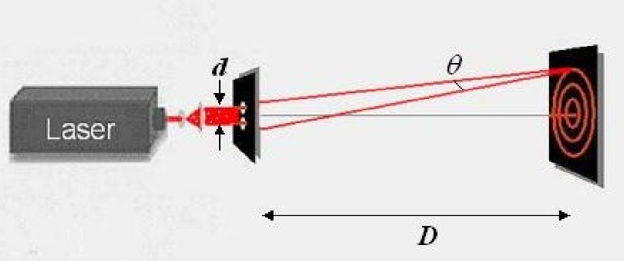
It contains only one specific wavelength. One can observe only one intensive colour (red, green yellow, UV, IR etc), depending on the type of laser and its laser media. We can compare with white light where all colors are present.



We will later discuss details about the monochromatic light and look at finer details of the laser spectrum. Since the laser consists of a cavity between two mirrors, we will have laser modes present, i.e. a number of different wavelengths present. However, normally the modes are so close to each other why we have to use high resolution spectrometers to observe these modes.

Laser light is coherent.

Light from a laser can be considered as a stream of wave packets moving in the same direction and having the same phase. They can be considered as well organized making it possible to deliver a beam with high intensity and small diameter.



Laser light has a high degree of directionality

The photons in a laser travel almost parallel to each other. We can give a simple explanation of the laser beams high degree of directionality and small beam size. Since the mirrors have high reflectivity (99.9% respectively 98%) the light travels some 50-100 times when leaving the exit mirror. In a large laser with cavity length around 1 m, the beam can be considered have traveled 100 m at a spot size around ¼ mm, corresponding to an angle of $\Phi \approx \frac{1mm}{400m} \approx 3 \times 10^{-6} rad$. A small laser has normally a divergence around 10^{-3} rad, or 1 mrad.

A Gaussian laser beam showing the 1/e2 point where r = w

Laser light can be focused to a smaller point compared to ordinary light. A test was made where a laser was directed towards the Moon. The light was spread around a 4 km diameter after having traveled 400,000 km. However, solid-state lasers often give conical beams with large divergence angles.

We calculate the divergence angle in the Moon experiment:

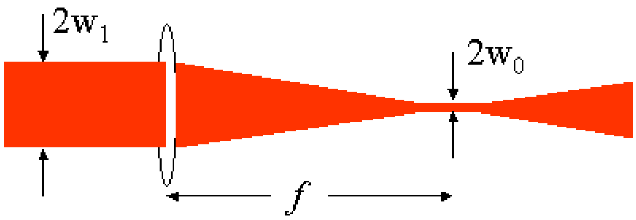
The angle is in radians: 4/40,000 rad = $1x10^{-5}$ rad

Laser light has can be focused to extremely small spots

The expression for a laser beam, a so called Gaussian beam, used in the TEM_{00} mode, when focused has a radius of:

$$w_0 = \lambda f/(\pi w_1)$$

Here w_0 stands for the radius of the laser spot obtained when the laser beam with wavelength λ is focused with a lens of focal width f, where w_1 is the radius of the incoming laser beam.



We can compare this expression with a setup consisting of an ordinary lamp focused through an opening, e.g. a circular aperture with diameter *D*. If one uses the formulae for diffraction one gets the following expression:

$$w_0 = 1{,}22\, \lambda f/D$$

When using the formulae for Gaussian optics, several equations can be derived that differ quite much from the corresponding formulae in classical optics.

Example

If we use a YAG-laser with wavelength 1064 nm, a laser beam with radius 1.0 mm and a lens with focal width 50 mm we get a laser spot having the radius:

$$w_0 = (1064\text{x}10^{-9}\text{x } 50\text{x}10^{-3})/(\pi\text{x}1.0\text{x}10^{-3}) = 17\ \mu\text{m}$$

Example

A green laser pointer can be purchased on the internet having a power of 200 mW with wavelength 532 nm. Its output beam diameter is 0.5 mm. Calculate the intensity in focus when using a lens with 20 mm focal diameter.

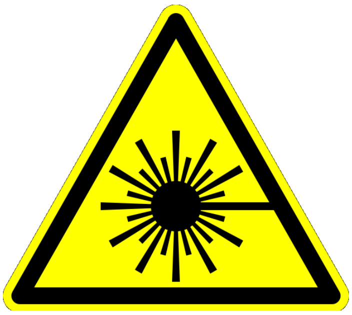
The spot size radius $w_0 = (532\text{x}10^{-9}\text{x } 20\text{x}10^{-3})/(\ \pi\text{x}0.25\text{x}10^{-3}) = 14\ \mu\text{m}$

The intensity in focus is $I = P/A = P/\pi r^2 = 200\text{x}10^{-3}/\pi(14\text{x}10^{-6})^2$ W/m^2 = 3.2 10^8 W/m^2. This is an extremely high power density.

Example

A green laser pointer can be purchased on the internet having a power of 200 mW with wavelength 532 nm. Its output beam diameter is 0.5 mm. Calculate the beam diameter 1.0 km away from the laser if the divergence is 1 mrad as it is in normal small lasers. The diameter of the circular laser spot at 1.0 km will thus be 1.0 m (D/L = 1.0 m/1000 m). This reduces the power to 200 mW (0.5x10^{-3} m/1.0 m) mW = 0.10 mW (Some lasers can have lenses that can focus the spot at larger distances).

Laser Power Classification



This is the type of warning sign for Class 2 lasers and higher classes. It has to be mounted outside a laser laboratory.

Classification of lasers

A classification was early created since the advent of the laser in 1960. Roughly we have four different *classes* of lasers depending on their effect on the eye:

Class 1

These types of lasers are under normal conditions safe to use. One often discusses the exposure. The maximum permissible exposure (MPE) is not possible to pass.
In the case of pulsed lasers, the maximum emission is related to the pulse duration as well as degree of spatial coherence.
These types of lasers are safe for use. However, when applying magnifying lenses, telescopes or microscopes in both directions, they can be hazardous. The so called Class 1M lasers give large diameter beams, or perhaps beam that diverges. If optics is used to narrow the beam, the MPE for a Class 1M laser can be exceeded.

Class 2

This laser is safe to use since the human blink reflex will reduce the exposure to around 0.25 s. It is restricted to visible light lasers (400–770 nm). The limitation of power is 1 mW cw, or more, if the emission time is less than 0.25 seconds or if the light is not spatially coherent. If one suppresses the blink reflex it could lead to eye injury. There are many so called laser pointers that are classified as Class 2. Laser pointers with power less than 5mW are most often safe to use. However, laser devices with power of 100 mW or more sold on the internet and can harm the eye.
Class 2 lasers can be harmful if one uses optics or optical instruments. The same rules hold as for the Class 1 lasers.

Class 3

A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the MPE can be exceeded, but with a low risk of injury. Visible continuous lasers in Class 3R are limited to 5 mW. For other wavelengths and for pulsed lasers, other limits apply.

Class3B

These types of lasers are hazardous also if the eye is exposed directly. However, diffuse reflections for example from a paper or surfaces are not harmful at all. CW lasers in the wavelength range from 315 nm to 10 μm are limited to a have an output power 0.5 W.
For pulsed lasers between 400 and 770 nm, the energy limit is 30 mJ. There are other limits that apply to other wavelengths and to ultra-short pulsed lasers (<100 fs = $100x10^{-15}$ s). The Class-3B lasers have to be supported by a key switch and a safety interlock (when one opens the lid of the laser).

Class 4

These lasers include all types of lasers having a beam power greater than that of the Class 3B lasers. They can burn the skin, and cause permanent eye damages. These lasers must be equipped with key switches and a safety interlocks. Most scientific, military, medical industrial lasers belong to this category, but also entertainment lasers.

These are labels sitting on lasers to show to what class they belong to.

Optical Density and L-Rating

When working with high energy lasers there is a need or preventing laser light to hit the eyes. Therefore, one uses laser goggles, most often applying the thin film metod.

When looking at laser safety, one often discuss two parameters; OD (Optical Density) and L-Rating. These parameters are used for an indication of the level of eye protection in different wavelengths regions. In the US one apply the so called ANSI standard. When studying eye safety one often calculates the transmission or *transmittance* (T) through the laser goggles. We define the Optical Density as follows:

$$\mathrm{OD} = \log\left(\frac{1}{T}\right)$$

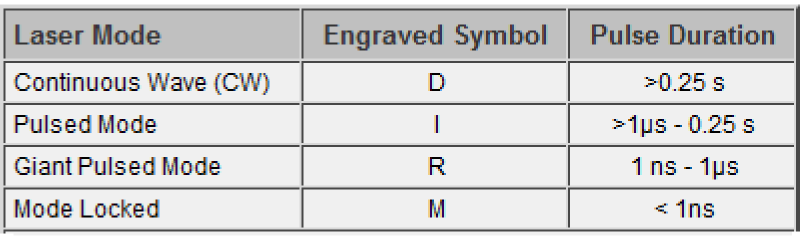
We can also rewrite this and express the transmittance (T) as:

$$T = 10^{-\mathrm{OD}}$$

CE CERTIFIED

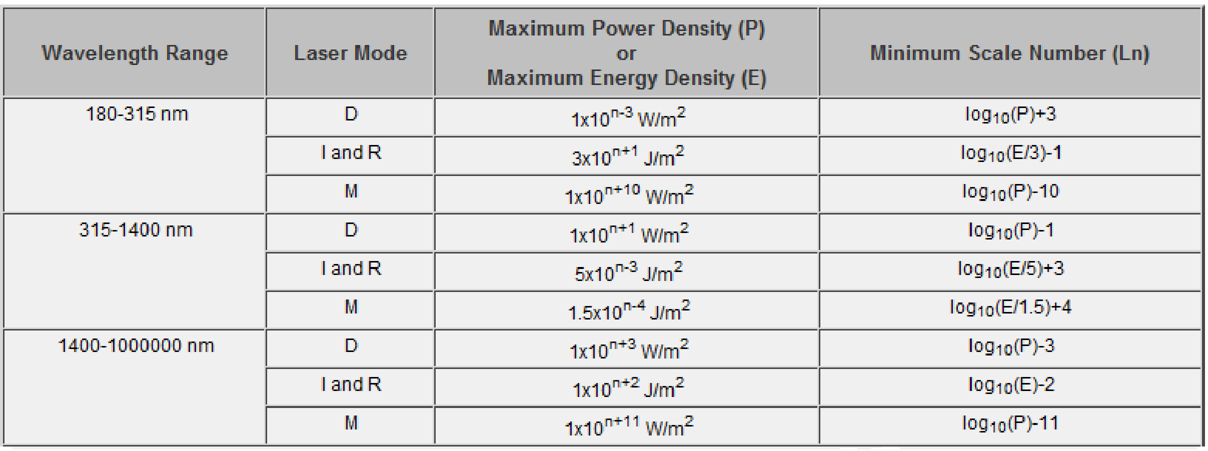
In Europe, the so called CE mark is used for the goggles or glasses used to show that the European standard (EN207) is applied. Also the L-Rating specifications have to be shown on the goggles. *The level of protection should be 10 seconds, alternatively 100 laser pulses that depend on the mode of the laser.*

The L-Rating depends on three parameters, i) wavelength range in nm, ii) laser mode notification (duration of the laser pulse) and iii) a so called scale number (*Ln*) that is intended to be used in together with wavelength range as well as the laser mode designation. All these parameters are used to secure that the laser safety goggles meets with the minimum required level of protection regarding a certain laser. CW-lasers (not pulsed) have the symbol D, whereas different pulses are notified by I, R and M depending on their pulse widths. We can look in the Table below for clarity



Laser Mode	Engraved Symbol	Pulse Duration
Continuous Wave (CW)	D	>0.25 s
Pulsed Mode	I	>1µs - 0.25 s
Giant Pulsed Mode	R	1 ns - 1µs
Mode Locked	M	< 1ns

When selecting laser safety goggles or glasses we can study the European norm for laser safety (EN 207 standard):



Wavelength Range	Laser Mode	Maximum Power Density (P) or Maximum Energy Density (E)	Minimum Scale Number (Ln)
180-315 nm	D	$1x10^{n-3}$ W/m^2	$\log_{10}(P)+3$
	I and R	$3x10^{n+1}$ J/m^2	$\log_{10}(E/3)-1$
	M	$1x10^{n+10}$ W/m^2	$\log_{10}(P)-10$
315-1400 nm	D	$1x10^{n+1}$ W/m^2	$\log_{10}(P)-1$
	I and R	$5x10^{n-3}$ J/m^2	$\log_{10}(E/5)+3$
	M	$1.5x10^{n-4}$ J/m^2	$\log_{10}(E/1.5)+4$
1400-1000000 nm	D	$1x10^{n+3}$ W/m^2	$\log_{10}(P)-3$
	I and R	$1x10^{n+2}$ J/m^2	$\log_{10}(E)-2$
	M	$1x10^{n+11}$ W/m^2	$\log_{10}(P)-11$

Example
Let us have a rating like 320-370 D L2 and >370-500 D L3. Then w have that at 370 nm the rating would be D L2 and for all wavelengths greater than 370 nm up to and including 500 nm would be rated at D L3. L2 means according to the table that L2=log(P)-1, why P = 10^3 W/m^2 since log(3)-1 = 3-1 = 2, which gives the Maximum Power Density (P).

Example
Let us have a cw Argon Ion laser lasing at 514.5 nm that has a maximum power density of $3.6x10^4$W/m^2. Applying the table above, the scale number can be calculated using *Ln*=log(P)-1, that gives *Ln* = log($3.6x10^4$) = 4.56-1 = 3.56 which we round up to the nearest integer 4 and obtain the *scale number L4*. In this case the LG4 laser safety glasses clearly meet the safety specifications of the European EN 207 standard.

Example
Evaluate *P*, the power density (intensity) in W/m^2 if we have an argon ion laser operating at 514.5 nm with the output power 320 mW with a beam diameter of 1.0 mm.
The intensity or power density in this case is just power/area unit = power/(πr^2) = $320x10^{-3}/(\pi (1.0x10^{-3})^2)$ W/m^2 = 102 kW/m2 = $1.0x10^5$ W/m^2.

Comment: Normally *P* stands for power (W) and *I* stands for intensity (W/m^2)

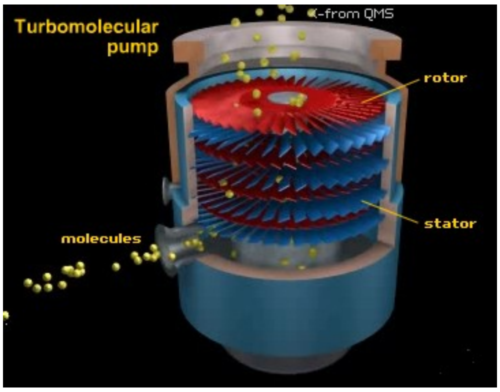
3.7 Electronic devices for pollution measurements

There are several devices available for low level measurements of pollutants such as Mass spectroscopy; Laser induced breakdown spectroscopy, nuclear and *eNose* techniques.

3.7.1 Mass spectrometry

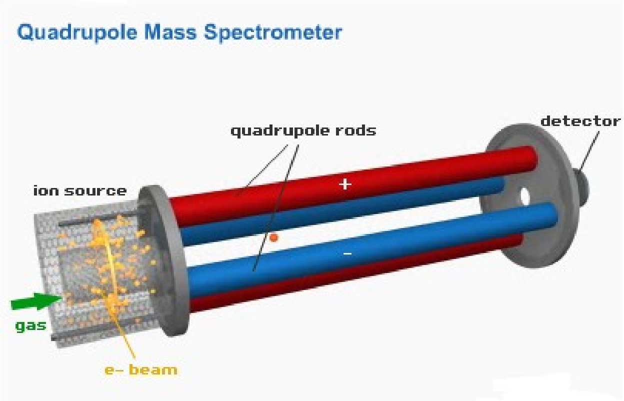
Determinations of masses of atoms and molecules have played a fundamental role in the development of modern atomic and molecular as well as nuclear physics. Thus, increasing accuracy in measurements of the masses M of the elements around 1920, showed that they were not exactly proportional to integer mass numbers A as earlier thought, but the difference

M-A was found to vary throughout the periodic system. This indirectly led to the discovery of the neutron and the modern concept of the atomic nucleus with fundamental applications to astrophysics, geology, archeology , energy production etc.
If molecules are bombarded with photons or electrons they break up in their atomic and molecular constituents which may be analyzed in a mass spectrometer yielding a unique "Fingerprint" of the studied molecule. Accordingly molecular mass spectroscopy is a very important tool in analytical chemistry , in medicine as well as in numerous industrial applications.

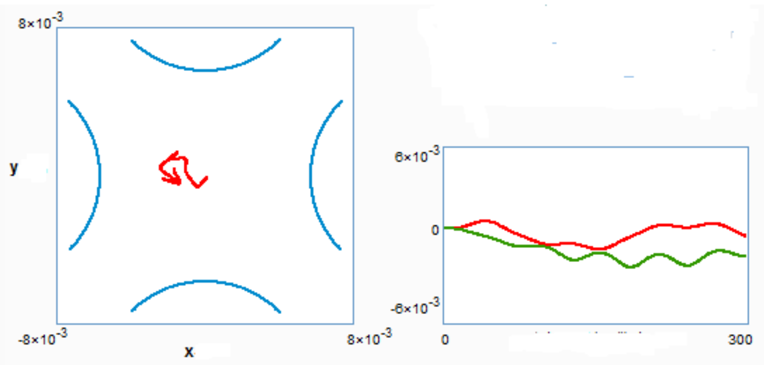


A mass spectrometer can be of different types, such as the magnetic mass spectrometer where the ions under investigation are bent in a magnetic field. The radius of the circular curve is directly proportional to the mass of the ion.
One can derive the following expression for the radius of the travelling ion:

Another type is the QMS, or mass quadropole spectrometer that consists of four parallel bars in the centre of the spectrometer. Different voltages are pot to the bars and the ions travel in an oscillatory way through the spectrometer. Depending on the settings of the voltages, the ions can pass through if their charge and masses are the correct ones for the voltage settings. The other ions hit the bars and do not reach the detector. In order to reach low levels of pressure in the QMS, turbo molecular pumps are needed as a second step after the ordinary rotary pumps. One has to reach a high vacuum in the QMS to avoid false spectra from the air the show intense peaks for N_2 and O_2 as well as water vapour, carbon dioxide and argon and other atoms and molecules with lower fractions.

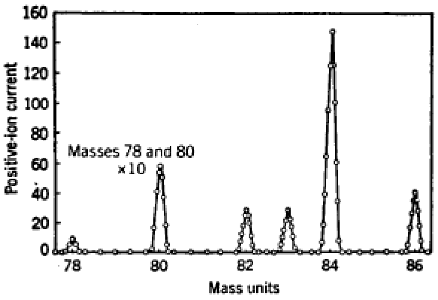


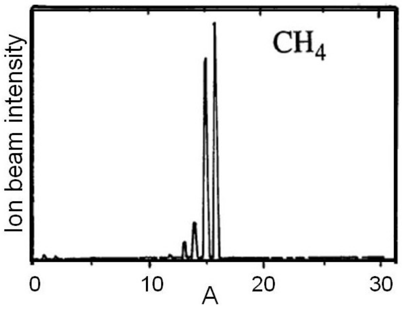
In the picture above we see the gas inlet, the electron beam for ionization of the gas, the four bars and an ion passing through the instrument towards the ion detector. In the picture below on can see the movement of a passing ion. It oscillates in both the x-and y-directions



In the left part one can observe the ends of the four rods. In this case the ion is coming towards us whereas the ion passes through the QMS as seen from the side. The computerized QMS gives the mass spectrum to be observed on a computer screen.

Below is show a mass spectrum of natural krypton, Kr, where the isotopic masses can be observed. The rare gas krypton has six stable isotopes. The odd masses with A = 79, 81 and 85 are missing since they are found to be radioactive and do not exist in Nature.





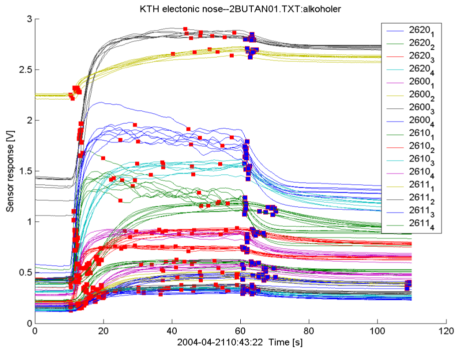
When recording a mass spectrum the molecules of the gas are hit y the electrons of the electron gun in order to ionize the molecule. This leads to dissociation of the molecule into molecular fractions and one has to be very observant to confirm what molecule entered the mass spectrometer. I the figure to the left, we see a spectrum of the CH_4 molecule.

3.7.2 Electronic nose, *eNose*

Electronic devices have been developed to detect explosives. Although the *eNose* is probably not as sensitive as a bomb dog, it has one feature that dogs do not have: It can distinguish between different explosives. The prototype is shown below to the left. It is a stainless steel tube with a fan in one end and 16 sensors placed along the sides. These sensors are small semiconductor devices, readily available from various companies. The KTH *eNose* works well because consists of several different sensors operating them at different temperatures (up to 750°C).

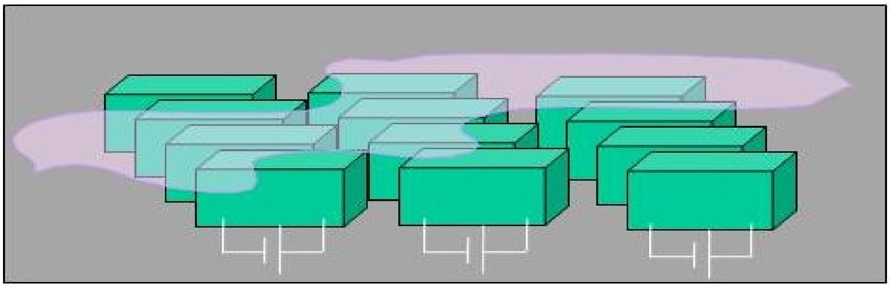
The electronic nose (left) and one of 16 sensor elements (right)

Different compounds give different fingerprints due to their different conductivity and other parameters. The same phenomena hold for patients expiring tumours or cancer molecules in small amounts. The signals from the sensors are processed with respect to rise times, etc. Although our system is not yet as sensitive as a dog's nose, we can, on the other hand, recognize the *type* of incident volatile molecules.



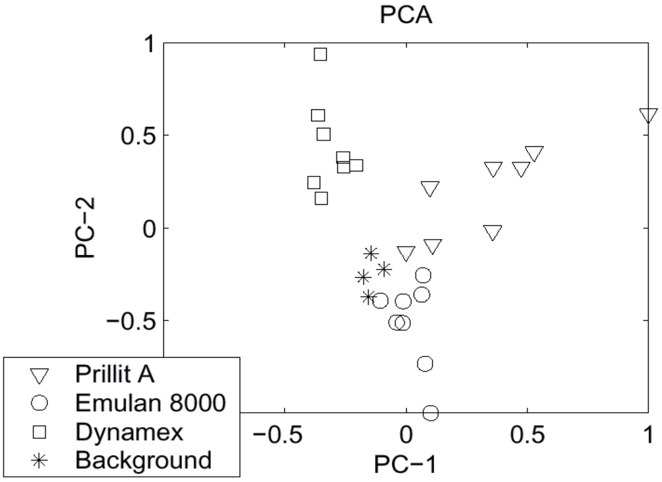
In the picture it is shown results when testing various types of compounds that emit substances that the nose is sensitive for. As a first test, we used our electronic nose on a series of cancer tumours from patients of the Sahlgrenska University hospital. Initially only 24 samples were used. When all but

one of these samples was correctly classified, we extended the exploratory test to about 162 samples. Totally 86% were correctly classified.
Examples of signals from the electronic nose above. The inlet valve is opened after 10 seconds and closed after one minute. Rise times and fall times as well as stationary max values are important inputs to the feature extraction algorithms.



The electronic nose consists of connected sensors working at different temperatures. A parameter as conductivity is measured and amnalyzed with various algorithms.

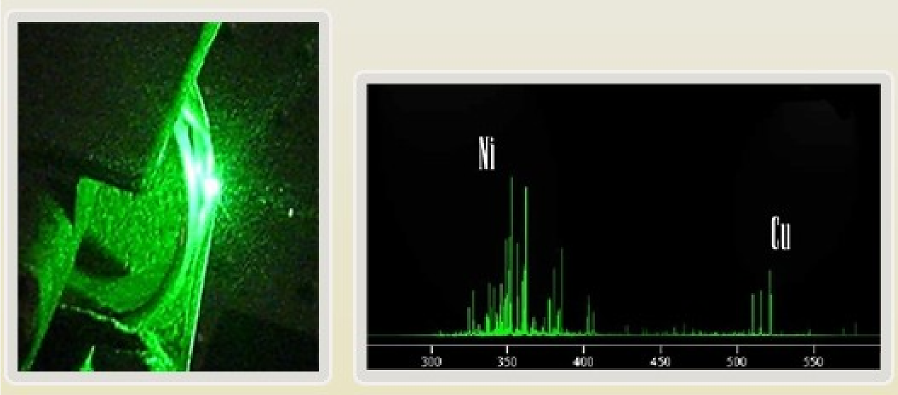
Normally it is enough to look at two rise times from the sensors to get 32 numbers for each case. By applying principal component analysis (PCA) and so called neural networks one can analyze the data and one obtains a diagram such as the one below, shown for explosives.



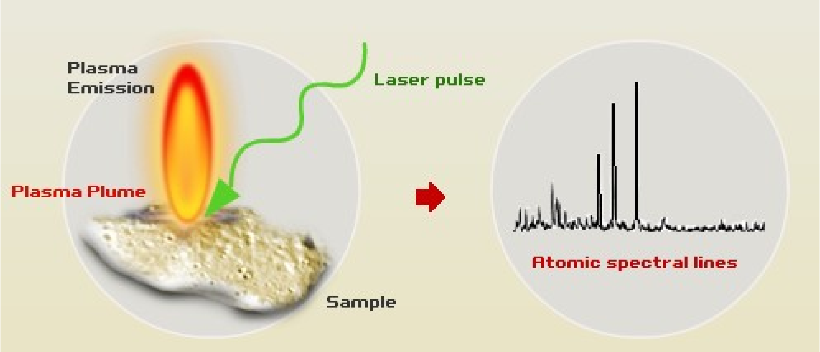
The electronic bomb project with the eNose gave the following result. One can observe three different types of explosives and the background.

3.7.3 LIBS

LIBS is an acronym for Laser Induced Breakdown Spectroscopy. It is a method used to determine the elemental (atomic) composition of various solids, liquids and gases.



LIBS can be used to make analysis of steel, metals and metal compounds but also to perform depth analyses of layers on steel surfaces and other metals. For instance one can make laser ablation a surface structure for a couple of minutes and determine the content of Ni, Cu, Pb and Fe. This method has a strong delectability and is very flexible concerning geometry and distance of analysis. It is possible to investigate how different elements vary, i.e. detection of compartments of materials and slay products.



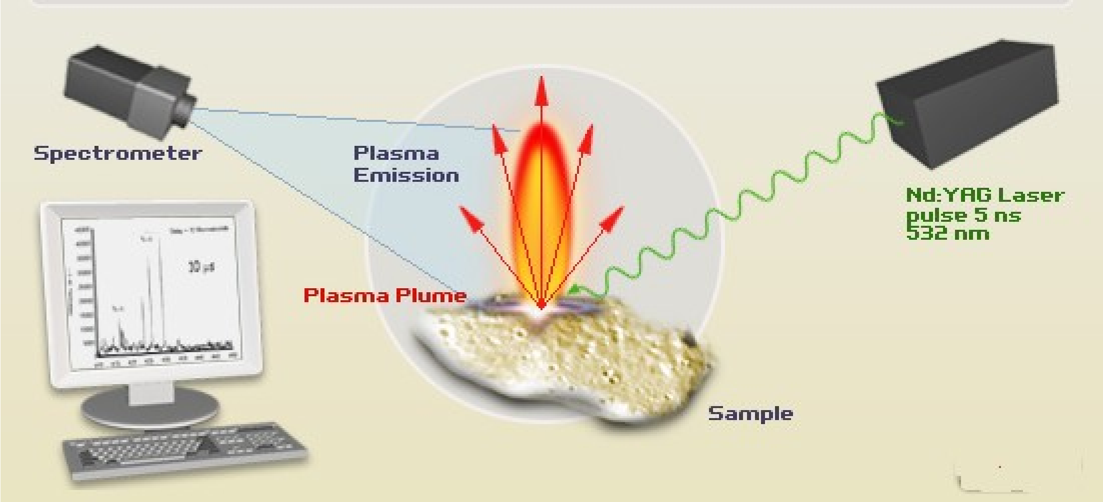
By focusing a high-power laser pulse onto a sample, a hot plasma or 'laser spark' is obtained and the emission from the atoms and ions in the plasma is observed.

The emitted light is collected by using fiber optics and is analyzed by a multiechelle spectrograph equipped with a fast ICCD camera. The atomic spectral lines can be used to determine elemental composition or elemental concentrations in the sample. The LIBS technique requires little or no sample preparation. Many attributes of the LIBS technique make it ideal for rapid on-site analysis of solids, liquids, or gases.

Advantages of the LIBS

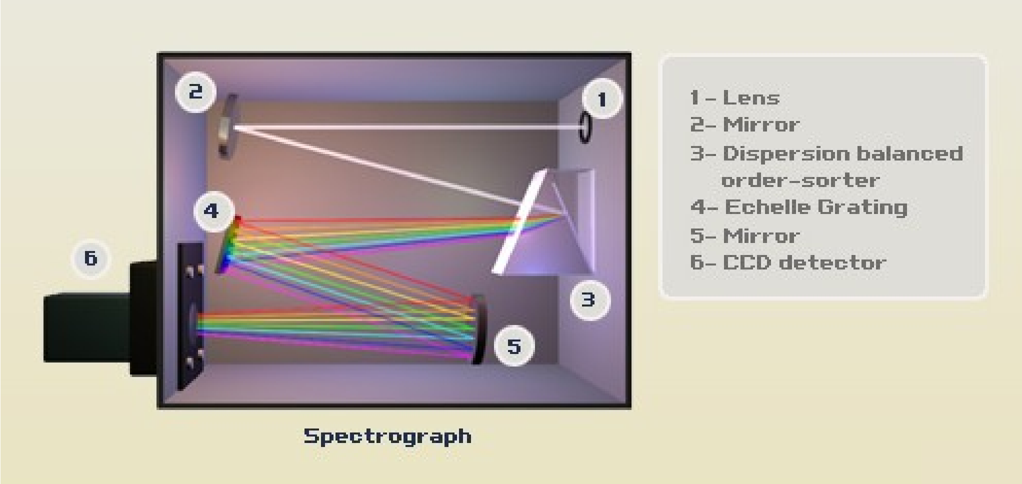
LIBS is a technique enabling analysis of solids, liquids or gases, with little or no sample preparation and very small sampling regions (~0.1 mg to 1 µg of material) can be investigated.

Also very hard materials can be studied and simultaneous multi-elemental analysis is possible. It provides simple and rapid analysis carried out in a single step.

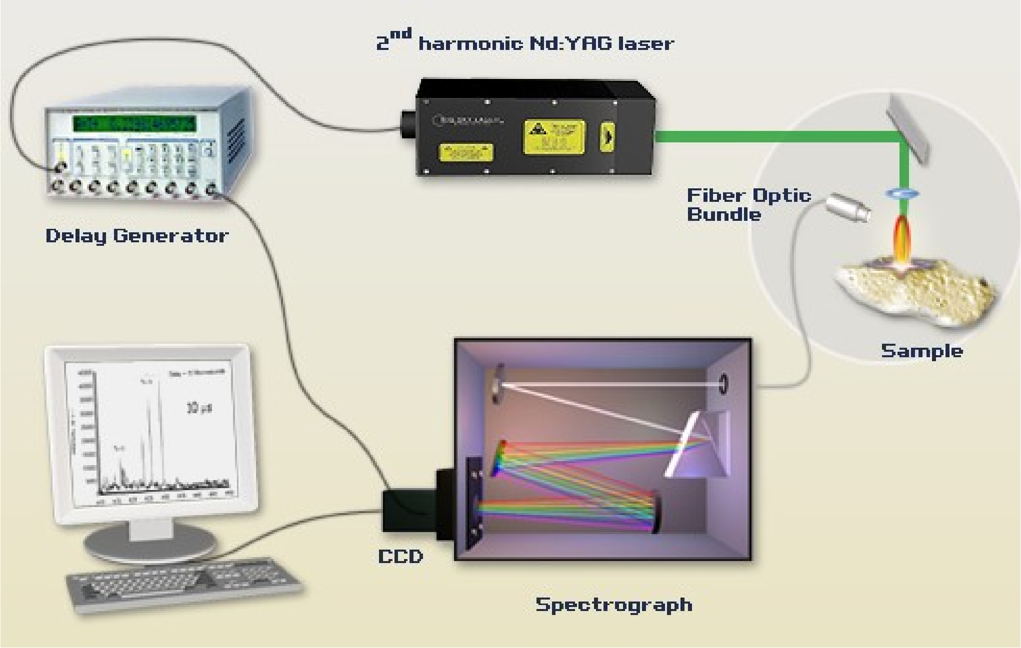


Laser-induced breakdown spectroscopy can be produced typically using pulsed Nd:Yag lasers, Excimer lasers or even femto-second lasers. The 5 to 20ns laser pulse with pulse energies around 10 mJ (YAG) produces a plasma plume that changes with time from the point of impact of the incident laser pulse. The plasma plume emission is collected by fiber optics and analyzed by the detection system.

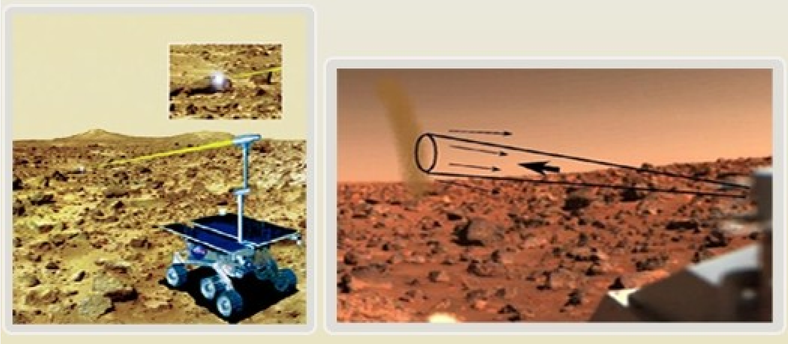
It is typically located at some distance from the sample to reduce the significance of self absorption or surface effects.
By applying an optical design that utilizes a so called Echelle grating which is combined with cross dispersion to separate the spectral orders of the grating. This combination results in several spectral segments, each covering a sub-range of the whole spectrum, and by using software the complete spectrum between 200-900 nm can be displayed.



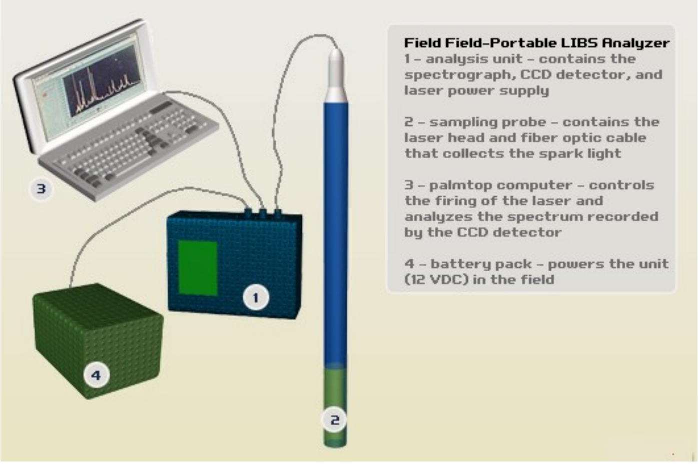
Below is shown a complete setup for LIBS:



The in situ LIDAR and LIBS device being developed under this task will provide a unique dataset which will contribute greatly to understanding the dynamics of the Martian atmosphere. This task will produce a compact, low-power Doppler LIDAR suitable for wind and opacity profiling of the Mars lower atmosphere from a lander. It is anticipated that the instrument will measure line-of-sight wind velocities to 1 m/s precision over ranges of 3-10 km, depending on the prevailing dust loading (i.e., atmospheric opacity). By LIBS measurements one can detect the elemental content of the environment.



There are commercial systems for measuring the content of soil for detection of various elements, shown in the picture below.



Field Field-Portable LIBS Analyzer

1 – analysis unit – contains the spectrograph, CCD detector, and laser power supply

2 – sampling probe – contains the laser head and fiber optic cable that collects the spark light

3 – palmtop computer – controls the firing of the laser and analyzes the spectrum recorded by the CCD detector

4 – battery pack – powers the unit (12 VDC) in the field

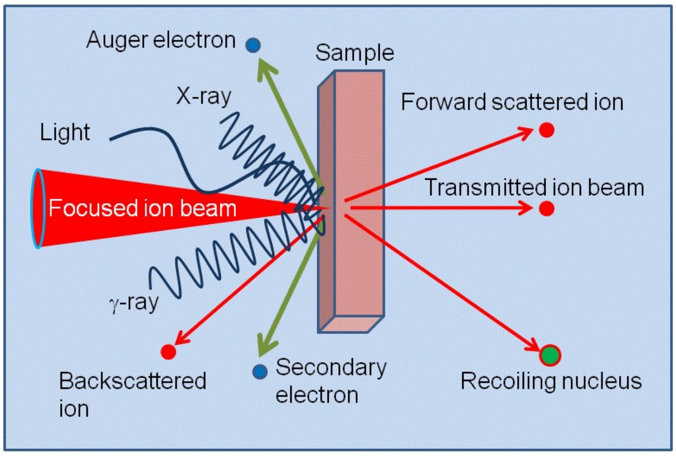
Details of how to operate is shown below:

Test of the field-portable LIBS analyzer
The probe is positioned on the ground and the laser (located in the bottom of the probe) is fired to make a measurement.

Laser firing rate	0.3 seconds between laser shots
Measurement time	45 secs/sample (for a 10 shot spectral average)
Set-up time	5 min. (includes 4 min. for detector cooling)
Weight	35 lbs. (includes battery pack)
Wavelength selection	via fixed screw pins for different spectral regions
Spectral range	250–600 nm (2400 l/mm grating)

3.7.4 Nuclear techniques for trace elements detection

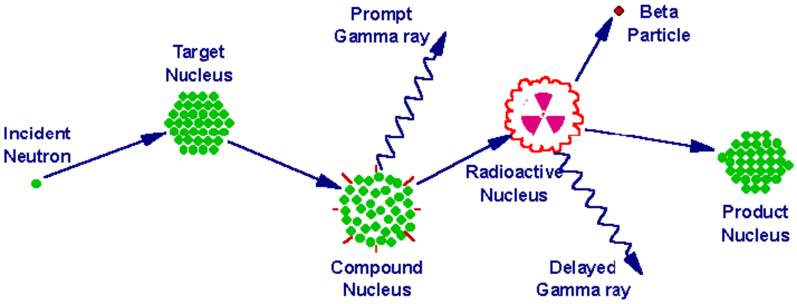
There are several techniques based on neutron activation, radioactive decay, neutron scattering and accelerator based methods, like Rutherford scattering and PIXE. Many of the nuclear methods are extremely sensitive. Trace element detection can be measured to levels below 10^{-12} g with good accuracy. The picture below shows an accelerator based method where an accelerator gives an ion beam that hits a sample and different effects can be measured.



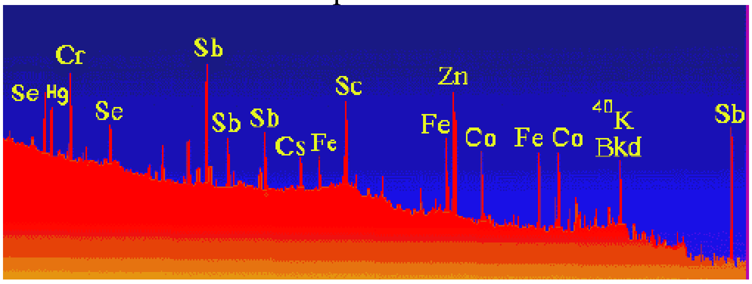
Neutron activation

This is a technique for material analysis where a sample is exposed for a flow of neutrons. The neutron flow is produced in a reactor, a neutron generator or a radioactive source like an Am-Be (Americium-Beryllium) source.

The atomic nucleus of the sample catches a neutron an unstable nuclide can be the result. The decay can give rise to characteristic γ -rays typical for the created isotope. The γ -rays can be detected in a high resolution germanium detector.



The picture above shows how the target nucleus gives various γ-rays that can be energy resolved and results in a spectrum like the one below.



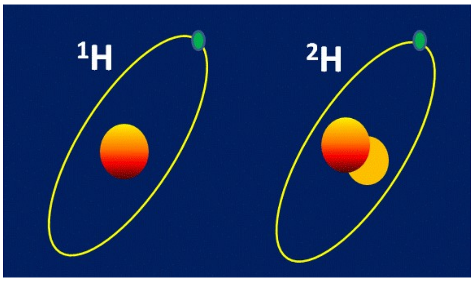
Here we observe intensity as a function of energy, where the specific elements are detected at different energies.

3.7.5 Isotopic quota and fractions

By measuring isotopic fractions of the elements, one can investigate environmental factors and for instance from where methane in the atmosphere has its origin on Earth

Introduction isotopic fractions

Most elements have several isotopes that are identical chemically, why their relative abundance, roughly are constant in Nature. However, their small mass differences give a small effect in chemical reaction velocities and physical processes. This can be used to investigate environmental factors.



The effects are largest for light elements, since the relative difference in mass is large (^1H and ^2H, mass 1 u and mass 2u), i.e. (2-1)u/1u = 100%, whereas for ^{12}C and ^{13} C has a relative difference of (13-12)u/12u = 1/12 = 8% .

For methane CH_4 with ^{12}C respectively ^{13}C we have a relative mass difference of (17-16)u/16u = 6%. These differences can be measured.

Chemical reaction dynamics

In a chemical reaction often chemical bonds are broken and created. One can discuss how the reaction speed is affected regarding the constituencies and atomic masses of the compounds.

A chemical bond can in a first approximation be compared with the force involved when two masses are connected by a spring. By applying quantum mechanics one finds that the vibrational energy of a diatomic molecule is given by

$$E_v = \omega_e \left(v + \frac{1}{2} \right)$$

Where $v = 0, 1, 2, ...$

The vibrational constant ω can by comparing with the mechanical picture de derived as

$$\omega = \sqrt{\frac{k}{m}}$$

This shows that small masses give higher vibrational frequencies and vice versa, which also can be connected to the ability for chemical reactions. Also evaporation and diffusion are mechanisms where molecules with small masses are easier to evaporate and much easier diffuse through different media. So, these effects influence isotopic differences between molecules where we realize that lighter isotopic elements have larger differences than heavier.

Isotopic fractions of hydrogen and oxygen isotopes

The constituencies of water, hydrogen and oxygen, can be used as isotopic probes to measure environmental factors, such as temperature. By studying isotopic fractions of ice, taken from drilled ice cores, temperatures on Earth in the past can be revealed. Hydrogen has two stable isotopes, ^1H and ^2H with the relative abundances 99.985 % respectively 0.015%. Oxygen has three stable isotopes, ^{16}O, ^{17}O and ^{18}O with relative abundances of 99.76%, 0.038% and 0.20%.

Isotopic fractions of carbon isotopes

Carbon is the most important constituent of organic molecules and their relative abundance of the stable carbon isotopes. For instance the carbon dioxide in the atmosphere can be studied revealing the biological origin behind the creation processes of CO_2. Carbon has the stable isotopes ^{12}C and ^{13}C with relative abundances 98.89% and 1.11%.

Isotopic fractions are defined relative a standard sample.
We define isotopic quota as;

$$\delta\, {}^{2}H = \frac{\left[N({}^{2}H)/N({}^{1}H)\right]_{sample} - \left[N({}^{2}H)/N({}^{1}H)\right]_{s\tan dard}}{\left[N({}^{2}H)/N({}^{1}H)\right]_{s\tan dard}} \times 100$$

$$\delta\, {}^{18}O = \frac{\left[N({}^{18}O)/N({}^{16}O)\right]_{sample} - \left[N({}^{18}O)/N({}^{16}O)\right]_{s\tan dard}}{\left[N({}^{18}O)/N({}^{16}O)\right]_{s\tan dard}} \times 100$$

$$\delta\, {}^{13}C = \frac{\left[N({}^{13}C)/N({}^{12}C)\right]_{sample} - \left[N({}^{13}C)/N({}^{12}C)\right]_{s\tan dard}}{\left[N({}^{13}C)/N({}^{12}C)\right]_{s\tan dard}} \times 100$$

The standard sample of carbon comes from a 100 million years old Mesozoic sample from fossils.

The ^{13}C effect

Isotopic fractioning of carbon is going on in the photosynthesis of plants.

- CO_2 passes from air into the plant cells by diffusion trough the cell membranes, which favours ^{12}C to ^{13}C, which in turn reduces $\delta^{13}C$.
- In the photosynthesis, ^{12}C is also favoured to ^{13}C, which further reduces $\delta^{13}C$.

Methane emission

By measuring $\delta^{13}C$ for a substance such as methane, one of the greenhouse gases, one can determine its origin.

- Emission of methane from cows results in a fraction coefficient of $\delta^{13}C$ varying from –6.0% to –6.3%
- Wet areas with mouldering plants emit methane with fraction coefficient of $\delta^{13}C$ varying from -5.9% to –6.2%
- Fossil fuels methane emission has a $\delta^{13}C$ varying from -1.5% to -5.0%

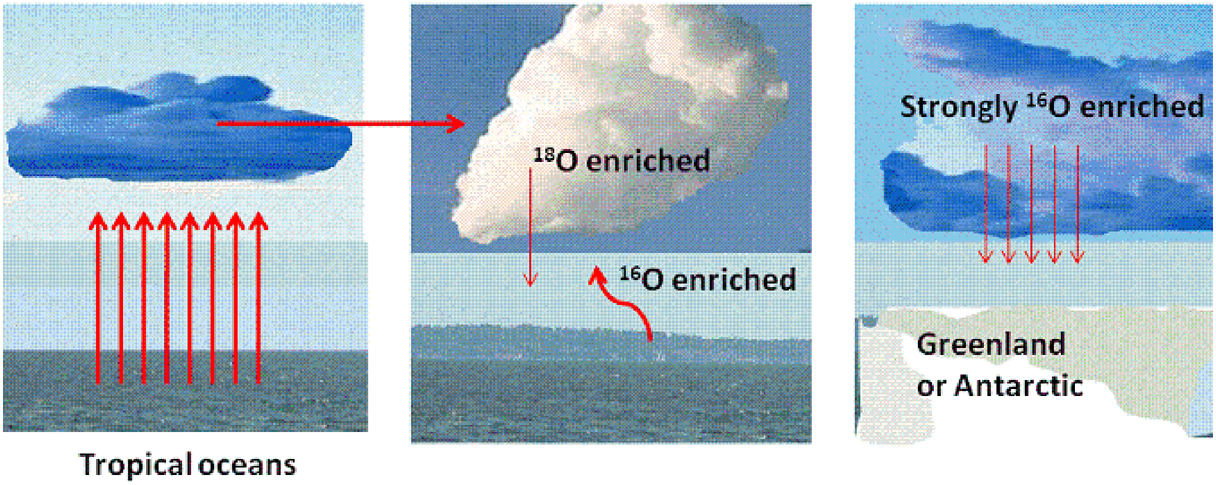
CO_2 emission

By measuring $\delta^{13}C$ for a substance such as carbon dioxide, also one of the greenhouse gases, one can determine its origin.

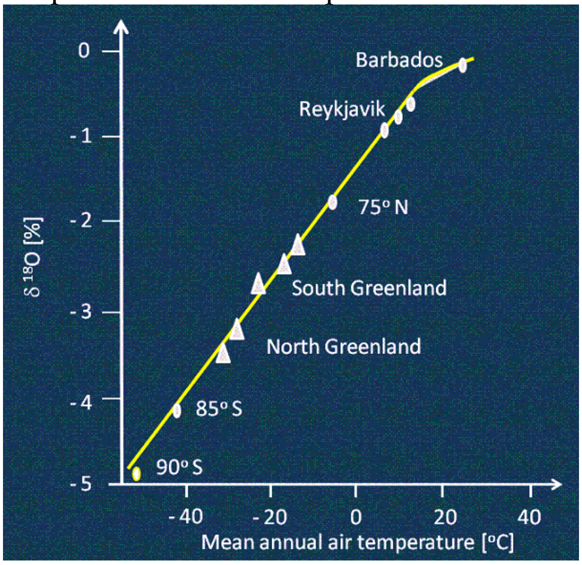
- Atmospheric $^{13}CO_2$ has a fraction coefficient of $\delta^{13}C$ of -0.7%.
- Fossil burning results in a $^{13}CO_2$ fraction coefficient of $\delta^{13}C$ of -2.8%.
- Carbon burning results in a $^{13}CO_2$ fraction coefficient of $\delta^{13}C$ of -2.5%.
- Natural gas burning results in a $^{13}CO_2$ fraction coefficient of $\delta^{13}C$ of -4.0% to -8.0%.

- Biomass burning results in a $^{13}CO_2$ fraction coefficient of $\delta^{13}C$ that is normally closer to zero than the above values.

Methane is an important greenhouse gas.
By studying methane concentrations in the atmosphere at different spots together with isotopic fractions of carbon one can determine from where the origin is.
By applying carbon fractioning one has for instance been able to determine that in the Netherlands 15% of the emission comes from fossil burning and the rest from modern biological materials such as wet areas, cows, garbage plants etc.
Oxygen fractioning gives information about climate changes.
Below is shown an example of fractioning of oxygen isotopes by vaporization and condensation. Since the temperature dependence of oxygen fractions is strong it can be used to trace climate changes. Isotopic fractions are being studied by looking at ice cores from Greenland and the Antarctic, 100,000 years ago.



In the figure below, isotopic quota of ^{18}O have been plotted as a function of mean temperatures at different places on Earth:



Example

One measured by mass spectroscopy the mass of ^{18}O in a danish air sample to be 0.20041 g. The content of ^{16}O of the same volume was 101.20 g. The standard ^{18}O/^{16}O ratio is 0.0020048. Calculate the $\delta^{18}O$ fraction coefficient in the spot where the sample was taken.

Solution

By applying the expression

$$\delta\,^{18}O = \frac{\left[N(^{18}O)/N(^{16}O)\right]_{sample} - \left[N(^{18}O)/N(^{16}O)\right]_{s\tan dard}}{\left[N(^{18}O)/N(^{16}O)\right]_{s\tan dard}} \times 100 \quad \%$$

We get $\delta^{18}O$ = 100 x(0.20041/101.2 – (0.0020048))/ (0.0020048) = -1.22%

Answer: -1.22%