Chapter 3
Sensing by Electromagnetic Radiation

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Abstract Electromagnetic radiation lends itself to non-contact sensing of many soil- and crop properties. The basis for this is that theoretically any matter – including constituents of soils and crops – can be identified by an electromagnetic index that is derived from its radiation. This electromagnetic index can act as an optical fingerprint of the respective matter or constituent.

Sensing from satellites or from aerial platforms allows obtaining maps that provide an overview within approximately the same time about soil- or crop properties from fields or from wider areas for tactical inspections. Sensors that are located on farm machines never can do this, let alone because of the time it takes to cover a wide area. Yet when it comes to the control of site-specific field operations, sensors on farm machines can provide the best spatial- and temporal precision that is possible. Their excellent spatial precision results from the low distance to soils or crops. The high temporal precision is possible since the signals are recorded just in time. This is important for those soil- and crop properties that vary fast in time.

Georeferencing by positioning systems allows storing site-specific signals.

Keywords Absorbance • Atmopheric windows • Clouds • Emitted radiation • Georeferencing • Optical fingerprint • Radar • Reflectance • Transmittance

3.1 Basics in Sensing by Electromagnetic Radiation

Site-specific operations require many samples, therefore, wherever possible, manual sampling should be replaced by autonomous- or semiautonomous sensing. This sensing can be accomplished with- or without direct contact to the respective soils

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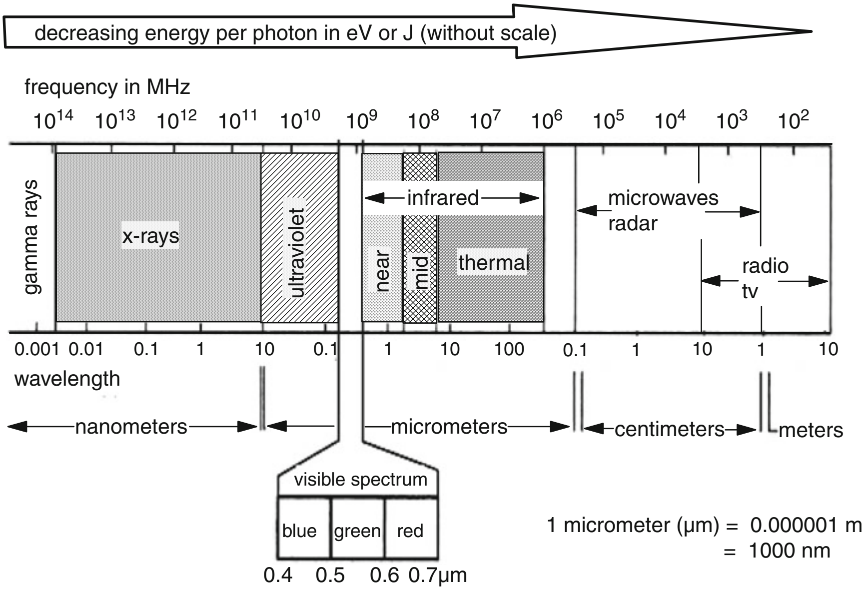

Fig. 3.1 Electromagnetic spectrum on a contiguous wavelength scale. Please note that the wavelength units change. The exact boundaries between radiation types are not unanimously agreed upon and thus can vary somewhat. Consequently, the limits between radiation types are approximates (From Chuvieco and Huete 2010, redrawn and altered)

or crops. Hence the methods can be classified into contact- or non-contact sensing. Either of these methods can be used when sampling occurs in conjunction with farm machines, whereas satellites and aerial platforms rely solely on non- contact sensing. Since only a few contact sensing methods are available, these are dealt with in appropriate chapters later. Non-contact methods almost exclusively are based on sensing by electromagnetic radiation. This chapter concentrates on this.

Electromagnetic sensing is based on **radiation** of photons. This radiation –depending on its specific type – carries energy through space along periodic harmonic waves. There are many different types of electromagnetic radiation (Fig. 3.1). An important criterion is its **wavelength**, which can vary between a tiny fraction of a nanometer and several meters. The wavelength times the frequency is the speed of the radiation. In a vacuum and in air, this speed is the same for all types of electromagnetic radiation, namely 300,000 km per second. Therefore, the shorter the wavelengths, the higher the frequencies are and *vice versa*.

Another important item is the **energy per photon**. This energy is proportional to the frequency of the radiation type and consequently inversely proportional to the wavelength. The shorter the wavelength, the higher is the energy per photon. The energy of very short wavelengths – ultraviolet radiation and shorter – therefore can be dangerous to human health. Yet this depends on the particular situation.

The differences in energy per photon also have implications for sensing. For photons from longer wavelengths, either very sensitive sensing devices are needed or a larger area is required in order to get a sufficient amount of energy. Thus a balance between wavelengths and spatial resolutions might be necessary. If a high spatial resolution is aimed at, using radiation from a short wavelength range in principle would be advantageous. However, the spatial resolution is not the only criterion when wavelengths for sensing are selected.

Radiation may come from a natural source or may be artificially induced. The most important natural sources are the sun and the earth. The wavelengths of the radiation that is emitted by these sources depend on the respective surface temperature. Since this temperature is much higher on the sun than on the earth, the solar wavelengths are much shorter than the terrestrial ones. Practically all the solar energy flux to the earth is in the wavelength range between 0.15 and 4.0 μm; hence it consists mainly of ultraviolet-, visible- and some infrared radiation. The maximum energy flux of the solar radiation is in the visible wavelengths. On the other hand, the energy that is emitted from the surface of the earth is in the region from 3 to 100 μm, which is mainly in the thermal infrared range (Guyot 1998). In short, the earth emits long-waved, but it receives short-waved radiation. There is only a small overlap between emitted and received wavelengths.

However, this is a rather rough breakup of the energy fluxes and the wavelengths involved. It is important that the longer waves do not contribute much energy. A more precise view is obtained when considering what happens with radiation that is directed from the sun to the earth or *vice versa*.

3.2 Emitted, Absorbed, Reflected and Transmitted Radiation

It is important to distinguish between emitted-, reflected-, absorbed and transmitted radiation. **Emitted radiation** leaves the surface mass of the sun or the earth, as every body at a temperature above 0 K discharges photons. The higher the temperature is, the shorter the wavelengths are. Photons that hit a particle en route, rebound and change the direction. Hence these photons become **reflected radiation**. If the photons are not reflected, but instead of this provide energy for the matter that was hit – *e.g.* for heating or for photosynthesis – **absorbed radiation** is dealt with. Finally there is **transmitted radiation** that was neither reflected nor absorbed.

Instead of using the absolute values, it is often reasonable to relate the reflected, absorbed and transmitted radiation to the initial radiation. These related or normalized signals are denoted as **reflectance, absorbance** and **transmittance**. It should be noted that the initial radiation – from which the reflectance, absorbance and transmittance are obtained – can be but must not be at the stage of emission from the sun or the earth. The respective initial radiation can also be radiation that was already reflected or transmitted at an earlier stage, *e.g.* on its path from the sun to the earth. It just depends on what is regarded as the initial radiation.

The sum of the respective reflectance, absorbance and transmittance in fractions always adds up to 1 (one). So it suffices to measure only two of these radiation types, the third type can then be calculated. This is important since often the

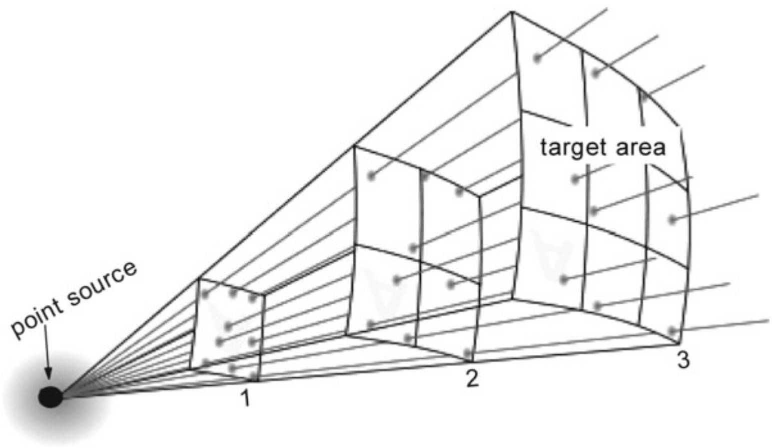

Fig. 3.2 Schematic to the effect of the inverse square law. The farer the target area is away from the point source, the lower is the number of photons per unit area

absorbance is difficult to measure directly. Sensing in precision farming mostly relies on reflectance from soils or crops. In a few cases, transmittance is used.

In theory, any matter – including constituents of soils and crops – can be identified either by its reflected, transmitted, absorbed or emitted radiation. The identification is a matter of careful **analysis of the spectrum** – that is the wavelength distribution – of the respective matter. This might include mathematical processing of spectral data. The fundamental basis of optical sensing is that in this way for every matter or constituent of soils and crops an **optical fingerprint** can be derived.

So far the best optical fingerprints have been derived from details in the visible- and/or infrared radiation. These details depend largely on the resolution of the optical signals and on the range of the spectrum that is used. The optical fingerprint might rely on the whole range of the visible, near-infrared and mid-infrared radiation, hence might be derived from a **full spectrum approach**. However, it can also be based just on a few or even only one narrow wavelength, thus depend on a **discrete waveband approach**. For some properties of soils or crops, such optical fingerprints have been well defined. There are also cases where research still has to find the best optical fingerprints. Details to this will be dealt with in later chapters.

If electromagnetic radiation emanates from a point source at a constant rate and the distance to the target (sensor) increases, the photons will spread out over a larger area. Hence the fewer photons will land on a target area of constant size, the farer this area is away from the source. This is the effect of the well known **inverse square law**, which states that the result per unit of the target area is proportional to the inverse of the squared distance (Fig. 3.2). Since the sensor of the electromagnetic radiation can be regarded as a target, this can affect the sensing results.

The attenuating result of the inverse square law on radiation is basically independent from any effects that are caused by material barriers such as molecules, which the photons might hit in the atmosphere. But these material barriers can induce additional attenuation.

However, there is another factor that affects the results on the target area and thus the sensing records as well. This is the **sensitivity** of the target area in the sensor to the energy of the radiation. A high sensitivity can compensate for attenuated signals. The progress that has taken place in remote sensing must be attributed partly to the fact that highly sensible receivers of the radiation have made up for inevitable effects of the inverse square law.

3.3 Atmospheric Windows and Clouds

The solar radiation that is directed towards the earth hits molecules and aerosols in the atmosphere. The result is scattering and absorption of radiation. Hence the radiation that finally gets to the surface of the earth is filtered by the atmosphere. However, this filtering effect of the atmosphere depends very much on the type of radiation. **Atmospheric windows** show, which radiation types are transmitted to the surface of the earth or *vice versa* (Fig. 3.3).

The respective white regions show, which radiation is transmitted. Black areas indicate radiation that is either absorbed or reflected back into space. The transmittance shown is for a sky without clouds.

There are two main regions of rather unimpeded transmittance: the range of the visible light and the range of the radar-, micro- and radiowaves. The situation in the infrared region depends on the respective wavelengths. Here ranges with blocked transmittance alternate with regions with rather free penetration. Thermal infrared radiation with long waves hardly is transmitted.

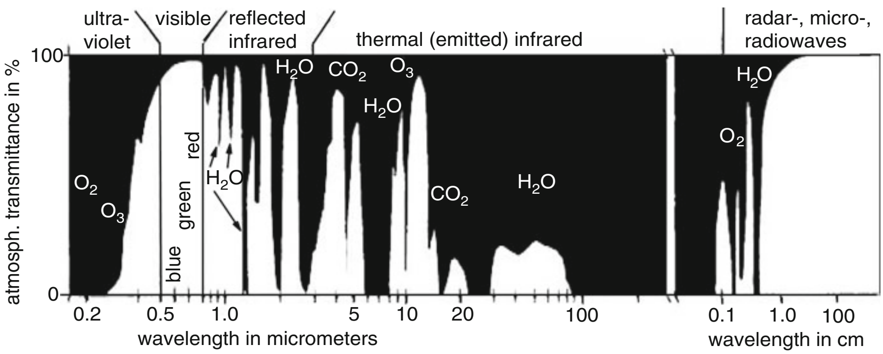

Fig. 3.3 The atmospheric windows (*white*) show the wavelengths that penetrate the cloudless atmosphere of the earth. The gaseous molecules that can block the transmission of wavelength ranges are indicated. For the boundaries between some radiation types, see legend to Fig. 3.1 (From NASA Earth Observatory 2010, altered and redrawn)

Table 3.1 Absorbance, reflectance and transmittance of the solar radiation spectrum by clouds (Data from Liou 1976, altered, transmittance added)

Type of cloud	Thickness (m)	Absorbance (%)	Reflectance (%)	Transmittance (%)
Cumulonimbus	6,000	10–20	80–90	0–10
Nimbostratus	4,000	10–20	80–90	0–10
Altostratus	600	8–15	57–77	8–35
Cumulus	450	4–9	68–85	6–28
Stratus	100	1–6	45–72	22–54

The gaseous molecules that block the radiation are oxygen, water and carbon dioxide. The transmittance of ultraviolet light is partly prevented by oxygen molecules, which is a blessing for human health.

The situation is quite different when **clouds** are present. Clouds are generated by water vapor near the condensation point. They consist of aerosol-sized particles of liquid water that absorb or scatter electromagnetic radiation of waves with less than about 0.1 cm length. Consequently only radar-, micro-and radiowaves are capable of penetrating clouds without being scattered, reflected or absorbed. This is a very important point for remote sensing, since in many areas of the world it is necessary to reckon with cloud covers.

So for sensing of visible- and infrared radiation by satellites, clouds can completely alter the possibilities. And on the average, clouds occupy regularly more than 50 % of the planet earth's atmosphere (Liou 1976). There are of course large regional differences in the incidence of clouds. Their attenuation of the transmittance depends on the wavelengths. Within the visible- and infrared range, the longer the waves, the more attenuation occurs. Short visible waves still have the best chance to penetrate the clouds and thus provide for some diffuse illumination of the earth's surface during an overcast day.

Even a thin stratus cloud reduces the transmittance on the average to almost one third (Table 3.1). With thick clouds, the transmittance drops to 10 % or less. The problem for recording data from satellites by visible and infrared reflectance is that indeed the terrestrial area might be regularly passed overhead, yet in regions with humid climate the actual sensing possibilities are not predictable.

3.4 Sensing from Satellites, Aerial Platforms and Field Machines

Electromagnetic sensing of soil- or crop properties can be achieved with passive- or active sensors. Passive sensors rely on natural electromagnetic waves that are provided either by solar energy or by radiation that is emitted from the earth. Hence passive sensing of visible light is confined to daytime. Active sensors have their own artificial radiation sources. This means that they can operate at night as well, even if visible radiation is needed for the sensing process. In case radiation outside the visible

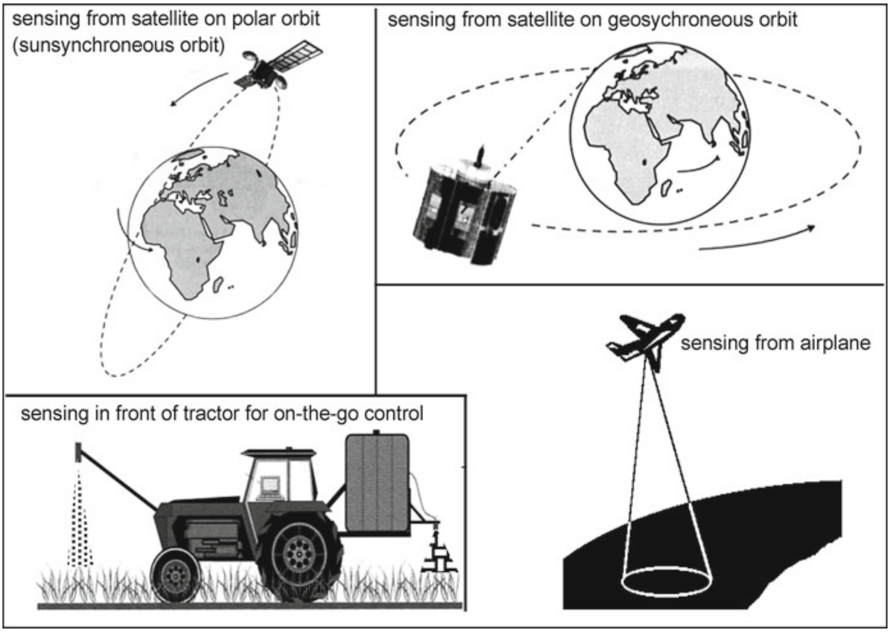

Fig. 3.4 Sensing from satellites on different orbits, from an airplane and from a tractor (From Chuvieco and Huete 2010 and from Heege et al. 2008, altered)

region is used, operation at night might be possible with either sensing system. But an important point with active- as well as with passive sensing can be the effect of the atmosphere of the earth on the radiation.

The reflectance of the soil or the crop must be transmitted to the sensor. So the distance between the sensor and the soil or crop must be dealt with. If the sensor operates on a tractor or another farm machine, the distance is less than 3 m. As a consequence of this short distance, attenuation of the radiation by the atmosphere hardly occurs. With satellites and also with aerial platforms, because of the very much larger distances, attenuation of the radiation takes place.

Satellites operate on different **distances** from the surface of the earth, depending on whether they move on a geosynchroneous- or on a polar orbit (Fig. 3.4).

In a **geosynchroneous path**, the satellites are always in the same position with respect to the rotating earth. Since these satellites orbit at the same angular rate and in the same direction as the earth, they appear stationary from the globe. The denotion therefore often is “geostationary satellite”. They orbit in an equatorial plane at an elevation of about 36,000 km and thus provide a big and constant view of the whole hemisphere in a single image. These satellite types are used for weather forecasting and for broadcasting.

Of special use for precision farming are satellites that either move on a polar orbit or those for the global positioning system (GPS). The latter will be dealt with in the next section. The satellites on a **polar orbit** circle the earth from pole to pole.

They do not rotate with the earth – as the satellites on geosynchroneous orbits do. Instead many of these satellites operate on a **sunsynchroneous path**, which means they pass the globe overhead at essentially the same solar time throughout the whole year while the earth rotates underneath them. So, theoretically, it is possible to get snapshots for specific places on the planet at the same solar time, which facilitates multitemporal comparisons. The elevation is between 200 and 900 km, hence much lower than with geosynchronous orbiting satellites.

For sensing from aerial platforms either a plane, a helicopter or an unmanned quadrocopter could be used. The latter has rotors like a helicopter, but four of them and can operate in an autonomous manner. With planes, the vertical distance can be several km, whereas for helicopters and especially for unmanned quadrocopters it can go down to 70 m or even less. So the attenuation of the radiation that is reflected from soils or crops can be much lower than for satellites.

The spatial- and temporal resolution that can be obtained is important. From theory, it must be expected that the **spatial resolution** decreases in the order farm machines, aerial platforms, satellites. And in fact, some years ago the spatial resolution that was obtained from satellites often did not satisfy the needs for site-specific farming. But steady advances in the sensitivity of optical instruments have improved the spatial resolutions. Today with a clear cloudless sky, satellites on polar orbits can provide spatial resolutions that make possible a terrestrial cell size of 1 m^2 and even less. This does not alter the general fact that it is easier to obtain a high spatial resolution when sensing occurs with smaller distances to soils or crops. Yet the situation is that with modern techniques and a clear cloudless sky, sensing from every platform can deliver the spatial resolution that is needed. Especially with optical sensors that operate from a farm machine, the resolution can be much higher than is even needed.

Concerning **temporal resolution**, sensing from satellites on polar orbits theoretically provides for the best prerequisites since data from the same field can be obtained every day, provided neither a closed atmospheric window nor clouds impede the radiation. It is practically not feasible to sense from farm machines or from aerial platforms with such a **temporal frequency**. This holds as long as farm machines and aerial platforms need drivers or pilots.

However, when sensing occurs from farm machines during a field operation, another important aspect deserves attention. Since many field operations take place just once or twice per year, the temporal resolution seems to be extremely low. But an important point is that with such proximal online and on-the-go control of farming operations, the sensing can occur exactly at the time when the information is needed. If there is temporal variation of soil- or crop properties during the growing season – and in many cases this is the situation – it can be important to sense precisely at the time when the farming operation takes place. So for these soil- and crop properties it is **temporal precision** that is needed rather than temporal resolution. A high temporal resolution might in these cases lead to a huge amount of useless data.

There are farming situations that call for a high temporal resolution or temporal frequency, *e.g.* when a crop is observed for pest infections. Yet there are also cases when temporal precision is the most important criterion, *e.g.* when in- season fertilizing of nitrogen takes place. This distinction between temporal resolution on the one hand and temporal precision on the other hand is helpful, though both might be needed.

With sensing from aerial platforms, it might be possible to avoid the transmission of signals through clouds by a low height above the surface of the earth. However, up to now unmanned observations from aerial platforms hardly occur. This limits sensing from aerial platforms. The development, permission and use of unmanned quadrocopters might alter the situation.

3.5 Microwaves or Radar Instead of Visible or Infrared Waves

Practically all sensing limitations that arise from atmospheric barriers (Fig. 3.3) including clouds are removed when **microwaves** are used. The name “microwaves” can be misleading, since their spectral region has the longest waves used in remote sensing. Hence the microwaves also have the lowest energy per photon. The limitations that arise from this for sensing from satellites are overcome by using **active sensors** with special antennas that provide a high sensitivity. The active sensors both emit microwave energy and detect its return from the ground. They are generally known as **radar** sensors. Radar stands for **r**adio **d**etection **a**nd **r**anging.

Modern spaceborne radar sensors work in the wavelength range of 0.1–100 cm and emit pulses of radiation in a “flashlight” manner. The signals that are reflected back to the satellite depend to a large extent on the roughness of the surface that was hit. The rougher the surface, the better the return signal is. Because from a rough surface, the radar echoes are scattered back in several directions. Hence the reflection is at least partly thrown back for recording, whereas specular reflection from a smooth target might not get back to the satellite at all. With cultivated soils, clods in the seedbed provide for a diffuse reflection (Fig. 3.5).

Yet the reflection back to the satellite depends on additional factors, especially on the wavelength and the dielectric properties of the soils or the plants. The longer the waves are, the more radiation is reflected back to the satellite and *vice versa*. Hence with long waves, a rather flat soil surface can appear as being rough, while with shorter waves it can show up as being smooth (CRISP 2010).

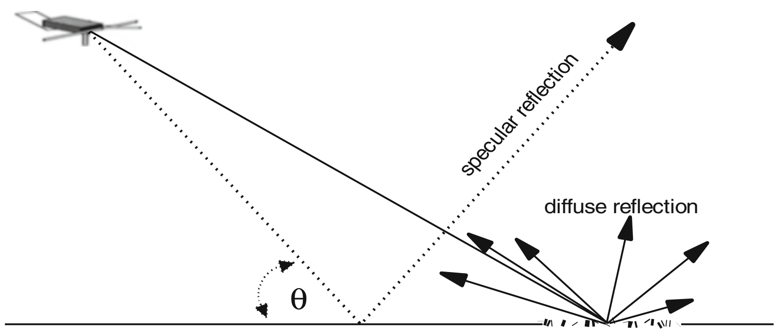

Fig. 3.5 Reflection of radar signals from a smooth- or from a rough target surface

Formerly, the dielectric properties have been defined by a so called dielectric constant. This property, however, is not constant at all, it varies widely. Consequently, now it is denoted as "**permittivity**". This physical term generally is expressed as relative permittivity because it is related to the permittivity of a vacuum and hence is without dimensions. It defines the potential to store electric energy. Air has approximately the permittivity of a vacuum, which is 1 (one). This is the minimum. Compared with other matters or materials, water has a very high permittivity of around 80. The respective data for dry natural materials including soils and plant matter are much lower, they are in the range of 3–8 (Paul and Speckmann 2004; Lillesand and Kiefer 1979).

These large differences in the permittivities or in the dielectric properties of water on the one hand and dry soils on the other hand are the base of **moisture sensing** by radar waves in precision farming. However, a prerequisite for sensing the moisture is that effects of differences in the surface roughness do not show up. Rather long radar wavelengths can help in this respect, at least with sensing of soils. This is because long waves react less on the roughness of the soil surface. Another advantage of rather long waves is their ability to sense the moisture not exclusively on the top surface of the soil, but instead also for some vertical distance down from the surface. The moisture solely on the surface of soils is hardly important for crops, since their water is supplied by a soil layer of some thickness.

The potential of sensing by radar waves can be enhanced by **polarizing the radiation**. The normal case is that the radiation vibrates or fluctuates in all directions perpendicular to the propagation at random, even if the wavelength is uniform. Polarizing the radiation aims at controlling the direction in which the photons vibrate. So a polarizer is a device that allows only radiation with a specific angle or a specific direction of vibration to pass through. The signal is filtered by a polarizer in such a way that the wave vibrations are restricted to a single plane that is *e.g.* perpendicular or horizontal to the direction of wave propagation (Fig. 3.6). There can be additional alternatives in polarizing directions.

It should be mentioned that this polarizing in a vertical- or horizontal direction does not alter the fact that every radiation has an electrical- as well as a magnetic field. These fields incidentally also move in perpendicular planes. Yet the polarizations shown in Fig. 3.6 only refer to electric fields.

When a polarized radar radiation is transmitted to crops or soils, it generates reflectance with a variety of polarizations. So – in a simplified way – there is again a somewhat random situation. But this random radiation too can be polarized again when it is received by the radar sensor. Today, many radar sensors are designed to transmit and receive waves that are either horizontally (H) or vertically (V) polarized. With these, there can be four combinations of transmit- and receive polarizations:

- HH – for horizontal transmit to the target and also horizontal receive
- VV – for vertical transmit to the target and also vertical receive
- VH – for vertical transmit to the target but horizontal receive
- HV – for horizontal transmit to the target but vertical receive.

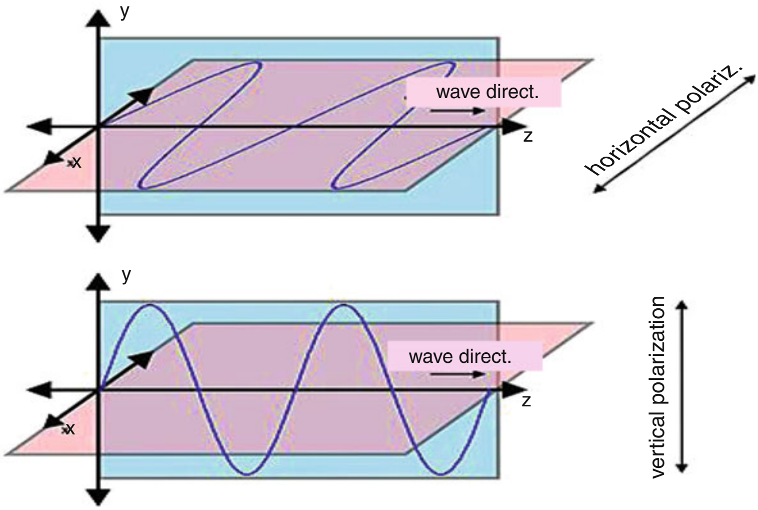

Fig. 3.6 Polarization of radar waves in a horizontal- or in a vertical direction (From Fink et al. 2010, altered)

Because the transmit and receive situations in the first two cases are the same, they are denoted as "**like-polarized**". The last two cases are "**cross-polarized**". These detailed sensing alternatives can – when used in combination with suitable wavelengths and incidence angles θ of the radiation (Fig. 3.5) – substantially improve the results obtained (Heinzel 2007; McNairn et al. 2009; Shimoni et al. 2007).

Yet whatever results are obtained when sensing with visible, infrared or radar waves, it should always be kept in mind that the signals indicate just phenomena that are of interest because of their known relation to soil- or crop properties. The signals never directly explain the reasons for the sensed phenomena. So still a clever mind is needed for the analysis of the causes. However, a farmer has to make this analysis too when he inspects his fields visually. The difference is in the amount and kind of data available.

And the success achieved with the large pool of signals often depends very much on an intelligent processing of these. It might be necessary to create special **mathematical indices** based on the respective electromagnetic spectrum. These indices are calculated from special selected wavelength bands by algebraic or differential operations. Suitable indices for soil- and crop properties have been and still are the object of intensive research. Some of them will be dealt with in later chapters.

However, there are still fundamental differences in the sensing potential of visible and infrared radiation on the one hand or radar waves on the other hand. This potential is listed in Table 3.2. Summing up, it can be seen that sensing with visible and infrared radiation is mainly focused at **constituents** of soils and crops, whereas the applications for radar waves are more pointed towards

Table 3.2 Feasible applications for sensing of soil-and plant properties by radiation

Radar waves	Visible- and/or infrared waves
Proven applications	
Volume or height of crops	Plant constituents, *e.g.* chlorophyll, water and nitrogen
Vertical- and horizontal arrangement of plant parts	Leaf-area-index of crops
Roughness of soil surface	Senescence of crops
Moisture of soil layer of a few cm	Organic matter and water on soil surfaces
Emerging applications	
Classification of crop species	Classification of crop species
Fresh biomass of crops	Soil texture on the surface
Dry biomass of crops	Soil content of some nutrients on the surface

getting information about **synoptical properties**, *e.g.* the volume of crops or the roughness of soil surfaces. Yet the items listed in Table 3.2 should not be regarded as strict limits (Kühbauch 2002).

3.6 Using Maps or On-The-Go Control in Real-Time

Aside from sensing limits, there are distinct differences in the domains of applications for properties that are recorded from satellites or from farm machines. Polar satellites can provide for maps that show the situation for a large area at a definite hour within a day. Machine based sensors never can do this.

There is a need for maps that provide for an **overview** of soil- and crop conditions at a definite time within a farm, a community, a county or a whole country. So overviews about *e.g.* soil water supply, fields that are fallow or cropped, crop species used, crop development, crop damage of various kinds (hail, drought, floods, diseases, insect infestation *etc.*), progress of harvesting and subsequent cultivation can be helpful. The present state of the art in sensing from satellites or aerial platforms allows not yet to provide all of these details despite the fact that the possibilities increase steadily. In many instances, combining of several radiation phenomena is needed in order to get to the desired information. Accordingly, McNairn et al. (2009) as well as Shimoni et al. (2007) have provided for methods in order to classify or identify crops that are grown in an area either by using visible- plus infrared radiation or by taking radar waves.

However, the information that is helpful differs. Governmental departments, farm agencies and agribusiness institutions need maps that provide for information over wide areas that include many farms. Farmers primarily require maps that either contain just the whole own farm or even are limited to a single field. So it is reasonable to differentiate between

- wide area maps
- farm maps and
- field maps.

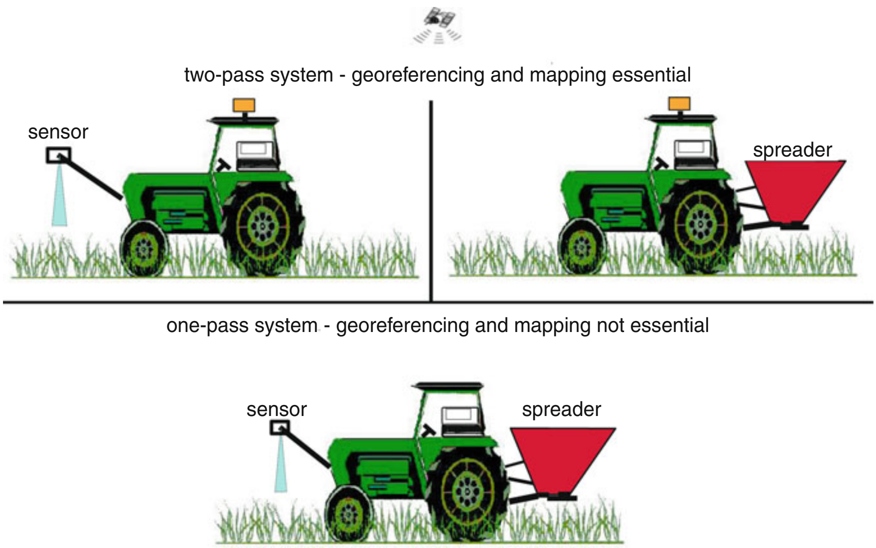

Fig. 3.7 Tractor-based control for site-specific spreading of fertilizer with or without mapping

Wide area maps and farm maps are predominantly used for **tactical inspections** of the situation. In a similar way like a mirror might allow to see around corners, these maps make it possible to get an overview of the coverage of large areas from a central bureau, and this within a few minutes. During the growing period, these tactical inspections can be useful in time intervals ranging from several days to several weeks, *e.g.* in order to see how the crops develop. The maps can be supplied easily and at reasonable cost via internet from polar satellites that orbit the respective areas every day. Limitations can exist in some agricultural regions for maps that rely on visible- and infrared radiation as a result of the effect of clouds (Sect. 3.3). Yet for some soil- and crop properties (Table 3.2), the cloud problem can be overcome by using radar waves instead of visible- and infrared radiation. The steady advances in sensing by radar waves facilitate this.

With field maps, the situation is different. They might sometimes be used for tactical inspections as well, but this is not the most important application. The preferential use in precision farming is for the control of **site-specific field operations.** Some properties that are recorded in field maps are temporally constant, others are not constant over time at all. Maps about texture, organic matter content and contour lines of soil can be regarded as being up to date for a long time and hence be used for many years. To a somewhat lesser extent, this also applies to maps about the pH of soils. But there are many soil- and crop properties that do not allow to use the same map for several consecutive field operations or years. The plant available nitrogen- and water content in soils can change within some days. The same applies to growth stages or infestations of crops with fungi or insects.

The ideal control technique for site-specific operations when the soil- or crop properties change fast in time is online **real-time sensing** combined with on-the-go adjustment of the farm machine (Fig. 3.7). This technique allows for the best temporal precision that is possible. An imaginable alternative to this would be online transfer of site-specific soil- and crop properties from satellites or from aerial platforms in real-time to moving farm machines. But this alternative is not yet state of the art with the exception of georeferencing (Sect. 3.7).

In addition, sensing from farm machines evades the cloud problem. This is important, since visible and infrared radiation – which is needed for site-specific control of field operations – is highly affected by clouds.

Online and on-the-go controlled field operations do not rely on maps. However, field maps of the respective operations can be created as by-products that allow *posterior* studies of the situations and also make possible a joint use in the control of subsequent field operations. A prerequisite for recording these field maps is the georeferencing of the signals, hence the simultaneous use of a positioning system. The next section will deal with this.

3.7 Georeferencing by Positioning Systems

Precision in mapping as well as in guidance of farm machinery needs georeferencing in the fields. Global navigation satellite systems (GNSS) provide the means for this (Fig. 3.8).

The most used and universally known method is the American global positioning system (GPS). In 1995, it was supplemented by the Russian GLONASS system. The GALILEO system of the European Union will start in 2014. A Chinese-and a Japanese system will also be created.

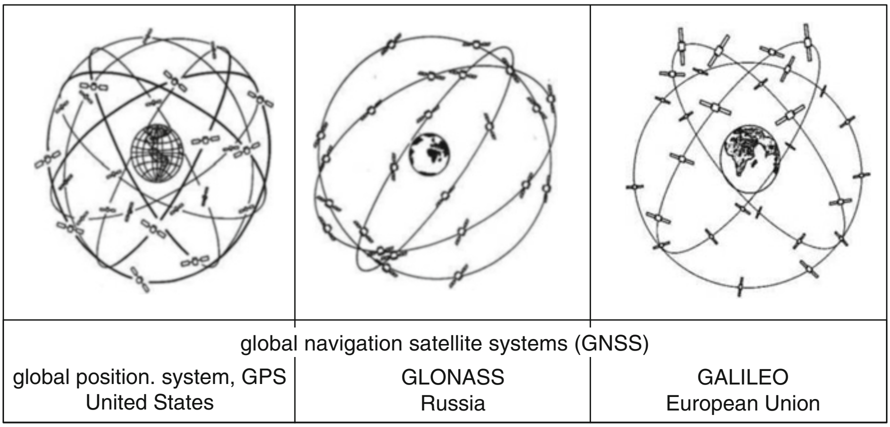

Fig. 3.8 Orbits used for present global navigation satellite systems (Graphs from Mansfeld 2010, altered and recomposed)

The American, Russian and European satellites orbit the earth about twice per day in oblique angles to the equator. The vertical distances to the surface of the earth are between 19,000 and 23,000 km. Hence the satellites move higher than those that are on polar orbits, yet lower than those on geosynchroneous orbits (Sect. 3.4). All systems use about 24 satellites, however, the GPS satellites are on six different orbits, the GLONASS- and GALILEO systems have only three orbits.

The signals are transmitted via **microwaves**, which operate within an atmospheric window (Fig. 3.3) and penetrate clouds. So obstructions in the atmosphere do not exist.

The georeferencing is achieved by the **time interval**, within which radio signals go from the satellites to the receiver. The latter is *e.g.* on a vehicle or on a farm machine that moves in the field. The satellites carry highly accurate atomic clocks. The receivers on the ground synchronize themselves to these clocks. Hence in a simplified way, every receiver too is a highly accurate atomic clock.

Once the time-interval is known that a radio signal takes from the satellite to the receiver on earth, the calculation of the respective distance between the satellite and the target is possible. This only requires taking into account the speed of the electromagnetic radiation (Sect. 3.1). And finally, when the distances between several satellites and the receiver are known, the geometric position of the target can be found out by trigonometric means. A prerequisite for this is the knowledge about the position of the satellites. This knowledge is at hand. Thus in detail, the signals can provide the target with four dimensions:

- the time
- the geographical longitude
- the geographical latitude
- the geographical altitude.

The last three dimensions together define the respective **geometrical position**. As a first step in precision farming, geometrical positions can be used for getting the borders and exact areas of all fields. Subsequently, the position can be used as the site-specific reference for all farming operations. This reference allows to link soil- and crop properties in an intelligent way. In this respect, the position is a benchmark in precision farming. The site-specific altitude can be used as a source for mapping the contour lines of fields. Topographic maps that contain this information can be obtained as a by-product of other site-specific farming operations (Abd Aziz et al. 2009).

Important criteria in georeferencing are the availability of the satellite signals and the precision of positioning. A general prerequisite of **availability** is that the radio waves from four satellites simultaneously can get to the receiver. Clouds are no barrier since microwaves are used, but trees and buildings can reflect the signals.

Whether this prevents georeferencing, can depend on the number of satellites that are operating (Fig. 3.9). This number has been steadily increasing, not least because the global positioning system of the USA has been and still is supplemented by similar systems from other parts of the world. Different global

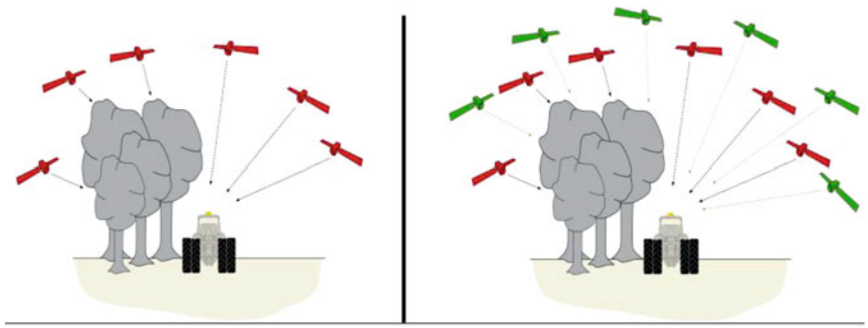

Fig. 3.9 The position of the receiver on the tractor is the same in both drawings. In the *left* drawing, the signals from only three satellites get to the receiver, which in most cases is not sufficient for georeferencing. In the *right* drawing – because of more satellites – georeferencing is possible (From graphs by Poloni 2009)

Table 3.3 Availability of georeferencing signals and maximal down time of receiver with varying numbers of satellites in orbit, which operate with a mask angle of 5°

Number of satellites in orbit	Availability % of time	Maximal total down time within 30 days (min)
24	99.98	8
23	99.97	13
22	99.90	42
21	99.10	386

Compiled from Mansfeld (2010), altered

navigation satellite systems provide signals that are compatible. Accordingly, one receiver can simultaneously use signals that come from separate systems.

The drawings in Fig. 3.9 show schematically the extreme situation when a farm machine moves along high obstacles of navigation signals. But also within a normal field without patches of trees it cannot be assumed that all the navigation signals have unimpeded access to the receiver. There always is a so called "**mask angle**" between the horizontal line in the field and oblique radiation that is oriented to the receiver. Oblique radiation that is directed to the receiver at an angle to the horizontal line that is smaller than the mask angle is ineffective. Apart from the situation close to forests or hedges, mask angles between 5° and 10° must be taken into account (Mansfeld 2010).

The data in Table 3.3 hold for a mask angle of 5°, hence for favorable conditions. The deteriorating effect of a lower number of satellites on the availability in % of the time appears to be rather small at first sight. However, the availability in % of time does not indicate the conditions for georeferencing in a way that is easy to understand. The maximal total down time – that can be calculated from the availability in % of time – provides for a better insight into the situation. It is the maximal sum of

Table 3.4 Inaccuracies and expenditures for different global positioning systems

System	Inaccuracy	Expenditures	
		Receiver (€)	Reference signal
Autonomous GPS, coded signal, single freq.	2–25 m	70–400	None
Differential GPS, coded signal, single frequency	1–3 m	1,000–3,000	0–500 €/a
Differential GPS, carrier phase signal, dual frequ.	10–30 cm	5,000–10,000	1,000–2,000 €/a
Real-time kinematic differential GPS	1–4 cm	20,000–40,000	None (own reference station)

time within a period during which signals cannot be received. This maximal total down time rises fast when less than 24 satellites are available (Table 3.3). The steady increase in the number of satellites that orbit the globe has helped to avoid problems that arise from this.

While having more visible satellites can reduce the down time of receiving signals considerably, it has only a slight effect on the **precision of positioning** or of **georeferencing**. This precision depends largely on techniques that are used for correcting errors.

In a strict sense, information that is given about the precision of georeferencing in metric units does not treat accuracies. Instead it is dealing with measurement errors, hence with inaccuracies or with imprecision. Generally, the lower the measurement errors, the higher the expenditures of the respective positioning systems are. Table 3.4 shows for some systems the ranges of measurement errors as well as the expenditures. All systems have the term GPS within their denotation because of the former leading position of the US navigation system. This does not mean that receivers cannot use signals from other global navigation satellite systems (Fig. 3.8).

The autonomous GPS system with coded signals and single frequency corresponds to the devices that are million times used in cars or small handheld computers. The measuring errors of these devices can be accepted for navigation on roads, however, for many precision farming operations lower inaccuracies are needed. For this, several ways are available.

A widely-used method is **differential positioning**. It involves having two GPS receivers. One of them is stationary and called the “base” receiver. Its geographic position is in the respective area – up to 200 km from the second receiver – and is precisely known beforehand. Hence this base receiver can register errors that are involved with signals from a satellite. As a consequence, it can provide the second receiver – which is the main receiver used for controlling a moving vehicle or a farm machine – with radio signals that have correction data. This allows for substantially lower inaccuracies (Table 3.4). The correction signals can be obtained online on-the-go either for an annual fee or sometimes also free of charge.

Another significant improvement in positioning can be realized – in a simplified way – by a higher resolution of the signals that the receiver gets. This higher resolution is provided by **carrier phase signals** instead of coded signals. Details to this are dealt by Mansfeld (2010) and by van Diggelen (2009).

An amazing good georeferencing can be realized by **real-time kinematic differential GPS**, abbreviated **RTK-GPS**. This system uses all the possibilities for improvement that are mentioned above and is – in the original way – equipped with an own base receiver for corrections. This base receiver is located rather close to the moving receiver. For farm machines, it often is positioned on the headlands. With optimal conditions, the positioning error can be as low as 1–3 cm. The inaccuracies increase with the distance between the two receivers. Per 1 km distance, the increase in error is about 1 mm (Heraud and Lange 2009). So even with a distance of 4 km, the inaccuracies can be below 4 cm.

RTK-GPS technology allows a farmer to return to the exact location again later during the growing season or even in subsequent years. Hence its precision in georeferencing can be relied on not only from pass to pass during a current farm operation, but from season to season or year to year as well. This feature is important when **repeatability** in the guidance of farm machinery via positioning systems with a low error is needed. Prime examples for this are the guidance for no-till sowing into inter-row strips of the crop from the previous year (Sect. 8.4.1) or strip-till sowing when the cultivating of the strips occurs in autumn and the sowing precisely into the center of the narrow strips in spring. There are additional examples when dealing with row crops. Some farmers pour concrete pads at the headlands to ensure that the base station is returned to the exact spot for precise guiding.

The maximum distance between the base receiver station and the moving receiver with real-time kinematic differential GPS – as described above – is between 10 and 20 km. This restriction in distance with an own reference station can be avoided by using an array or **network of RTK-GPS** base receiver stations within a wide area. The distance between adjacent **network base receiver stations** can be up to 70 km (Heraud and Lange 2009). These network base stations provide for correction data that are collectively processed. The result is that despite longer distances to the moving receiver within this network, a similar low error or inaccuracy as shown in Table 3.4, bottom is possible (Edwards et al. 2008). The transmission of the correction data from the network to the user typically is via mobile phone.

Not all precision farming operations require the accuracy or low error range of RTK-GPS. In many cases, the error associated with differential GPS operating on dual frequencies and carrier phase resolution can be tolerated. This system presently is used widely, since the expenditures are much lower than for RTK-GPS.

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