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REMOTE SENSORS

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1. Introduction

The term remote sensing is applied to the detection of objects and the determination of their position without making actual physical contact with them, that is, from distances between a few meters and many hundred kilometers. For detection and location we frequently use the effect which the objects have on certain kinds of fields, such as the gravitational or magnetic fields of the earth, or on the electromagnetic radiation field of the sun or other sources. The equipment used to measure variations in field strength is what we call sensors.

This paper is intended to give an outline of remote sensors using electromagnetic radiation, that is, measuring variations in the radiation field. Since we are here concerned with photogrammetric applications, we shall study only those sensors that form an image with the aid of electromagnetic radiation. These include photographic cameras, line scanners and side-looking radar.

Many papers have been published about these sensors, and there is also a number of more extensive works, such as the Manual of Remote Sensing published by the American Society of Photogrammetry (Falls Church, 1975), the first volume of which discusses the subject in great detail on over 500 pages. It is obvious that by comparison with the more comprehensive works, this paper cannot present any new aspects. Nor is this its purpose. On the contrary, it is intended to give the specialist engaged in evaluating photograms a concise outline of the operation of sensors in an attempt to provide some background information about the image-forming process as such. For this purpose, this paper will primarily deal with the technical and physical operation of sensors.

2. Atmospheric windows

Whichever method is employed for remote sensing of the earth with the aid of electromagnetic radiation, the latter has to penetrate the atmosphere of the earth. The transmittance of the atmosphere is a function of the wavelength of the radiation. In Fig. 1, the transmittance of the atmosphere is plotted against wavelength or frequency for a region from λ = 300 nm to λ = 3 m that is of interest for remote sensing.

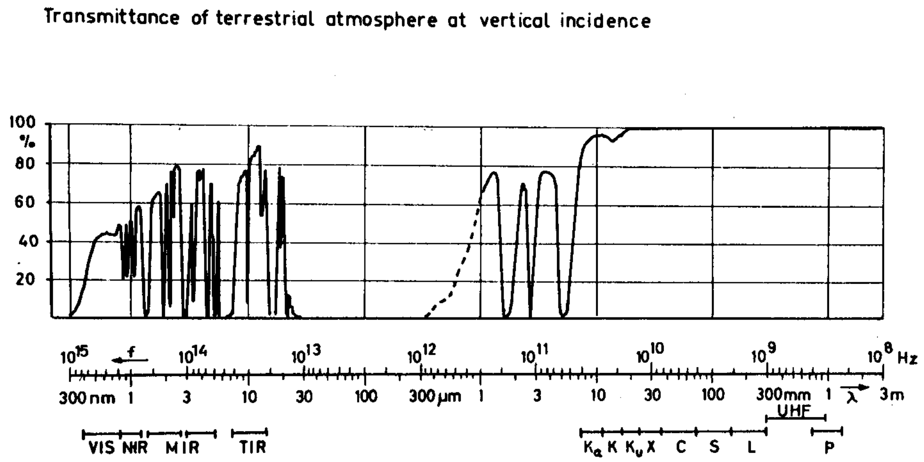

Fig. 1: Atmospheric windows

It is evident that there are regions of relatively good transmittance of the atmosphere - so-called atmospheric windows - between the absorption bands of the gases H_2O, CO, CO_2, NO_2, O_3 and CH_4. The window in the visible region (wavelength 400 nm $\leq \lambda \leq$ 700 nm) is marked "VIS" in Fig. 1, the window following in the near infrared region (700 nm $\leq \lambda \leq$ 1.2 µm) "NIR". These are followed by two windows at 1.3 µm $\leq \lambda \leq$ 3 µm and 3.5 µm $\leq \lambda \leq$ 5.5 µm, here marked "MIR" for middle infrared, and a window at 8 µm $\leq \lambda \leq$ 14 µm, marked "TIR" for thermal infrared. Finally, we have the radio window towards the long waves, starting at $\lambda > 1$ mm. Remote sensors use these windows, that is, wavelength regions of good atmospheric transmittance. No reliable data about atmospheric transmittance is available for the region from 30 μm $\leq \lambda \leq$ 1 mm, but this region has little to offer for image-forming sensors because there are no detectors with a suitably short response time for this region (see item 5). For the microwave region $\lambda > 1$ mm, Fig. 1 gives the designations of radar frequency bands below the wavelength scale.

Radar band	Frequency range
K_a	40 000 to 26 500 MHz
K	26 500 to 18 500 MHz
K_u	18 000 to 12 500 MHz
X	12 500 to 8 000 MHz
C	8 000 to 4 000 MHz
S	4 000 to 2 000 MHz
L	2 000 to 1 000 MHz
P	390 to 220 MHz

3. Radiation sources

Sources of electromagnetic radiation that may be used for remote sensing are natural sources such as the sun, earth, atmosphere and outer space on the one hand and artificial sources such as flash lamps, laser and microwave transmitters on the other. The sun and space can to a first approximation be considered as black bodies whose radiation is exclusively a function of body temperature and is governed by Planck's radiation law. In the wavelength region of thermal infrared, this approximation also holds for the surface of the earth. Fig. 2 shows the radiance of an ideal sun (temperature T = 5900 K), earth (T = 295 K) and space (T = 5 K), plotted against wavelength. As in Fig. 1, the wavelength and frequency scale covers eight powers of ten, while the division of the ordinate standing for brightness covers 28 powers of ten. The peak radiance for the sun can be found around wavelength λ = 500 nm, for the earth λ = 10 μm and for space around λ = 500 μm.

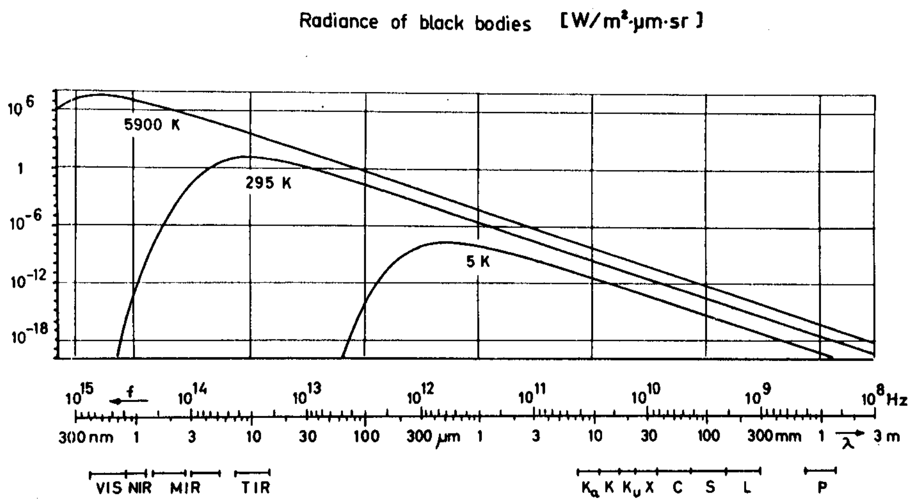

Fig. 2: Radiance of ideal sun, earth and space

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However, in remote sensing of the earth we are not interested in the "brightness" of the sun or space, but in the "brightness" of the terrestrial objects irradiated by the sun or by space. If we use as ideal terrestrial objects a black body and a white Lambert reflector, that is a body characterized by perfectly diffuse reflection of all incident radiation, we obtain the diagram according to Fig. 3.

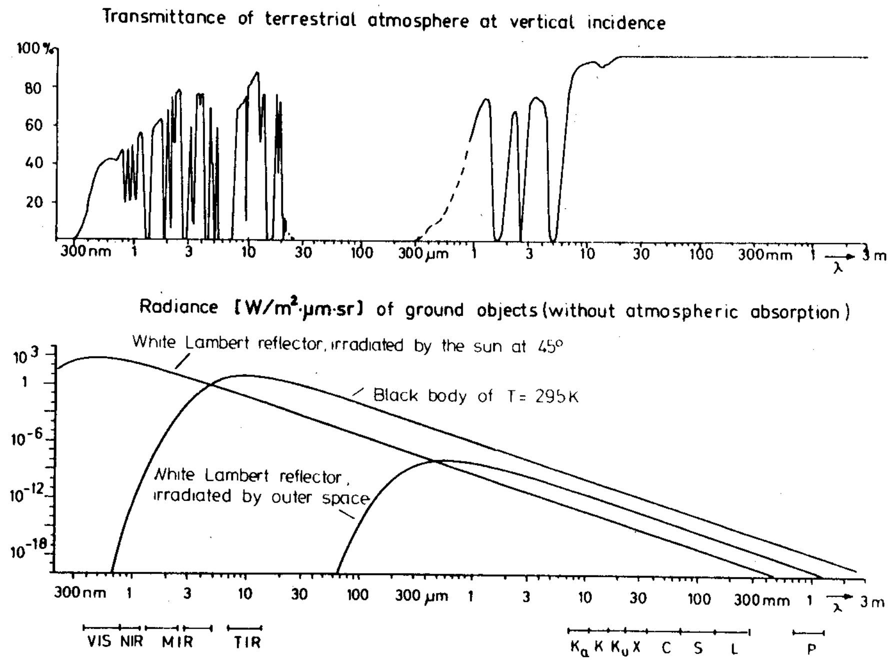

Fig. 3: Transmittance of terrestrial atmosphere and "brightness" of ground objects

This diagram shows that in the VIS and NIR regions the radiation emitted by terrestrial bodies is less than the reflected solar radiation by many powers of ten. In other words, it will be completely impossible to tell the temperature of terrestrial objects from infrared photography ($\lambda \leq 900$ nm). Only in the middle infrared region (MIR), reflected solar radiation and emitted radiation reach about the same level. In the thermal infrared (TIR), the radiation emitted by the objects predominates. In the microwave region from about $\lambda \geq 450$ µm, the reflected space radiation is stronger than the diffusely reflected solar radiation because space radiation is incident from the entire hemisphere, while the radiation from the sun is limited to a very narrow solid angle. For black terrestrial objects emitted radiation predominates in the microwave region, while for objects of higher reflectivity it is reflected space radiation.

While we may consider the sun, earth and space (with certain restrictions) as black bodies, this in no way applies to the atmosphere and the most popular artificial radiation sources. The atmosphere radiates only in wavelength regions in which transmittance is low. And this is precisely why these regions cannot be used for remote sensing of terrestrial objects. In the atmospheric windows, however, the radiation emitted by the atmosphere is only weak. Here, the atmosphere does not act as an "illuminating" source but as an error source at best. An exception is the short-wave region of 300 nm $\leq \lambda \leq$ 700 nm where the atmosphere does not absorb but scatters the sun's radiation. The intensity of this scattered radiation - so-called sky light - is greatly influenced by wavelength (Rayleigh's scattering coefficient proportional λ^{-4}). In the short-wave region, sky light has a considerable share in overall illumination.

Artificial radiation sources operate only in a narrow wavelength region (microwave transmitters, laser) or in several narrow wavelength regions (gaseous-discharge flash lamps).

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4. Object characteristics and photographic information

Fig. 4 lists the parameters affecting picture content and the possibilities of evaluation. The physical parameters are "illumination" (or irradiance, to be precise) of the object by an external source, the temperature of the object and its properties of reflection and absorption. The objects are imaged either by the radiation they reflect or emit or by a mixture of emitted and reflected radiation. Which of the two components is predominant depends on the wavelength region, as has been shown in Fig. 3, but also on the temperature and absorptivity of the object. Absorptivity is always identical to emissivity, that is, an object that is "black" in a certain wavelength region will absorb well and also emit a considerable amount of radiation itself. The "reflection" parameter describes the type of reflection (diffuse or regular) as well as the polarization of the reflected radiation.

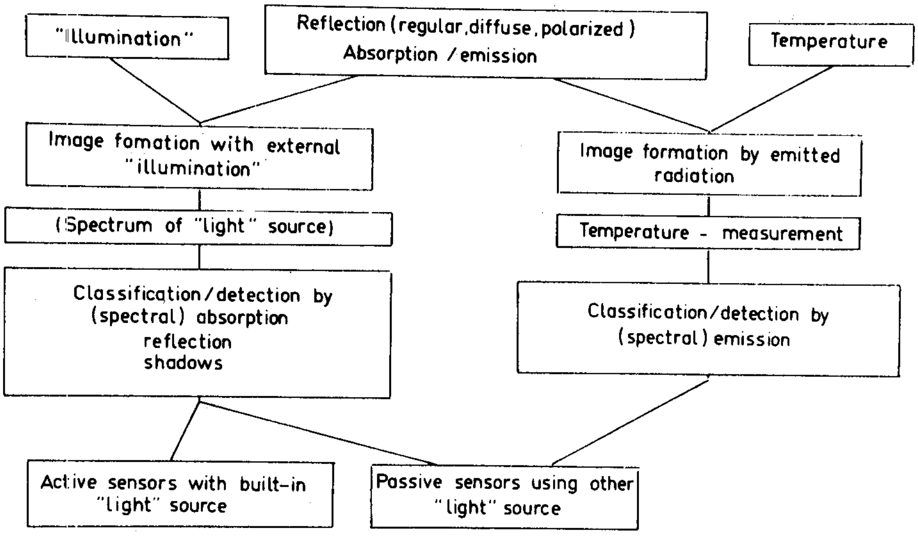

Fig. 4: Parameters of image formation and image information

If outside "illumination" is used for image formation, the reflected radiation may be employed to measure the spectrum of the radiation source, which however is hardly of interest in remote sensing of terrestrial objects. Here, we are primarily concerned with detecting or at least classifying objects. For this we use parameters such as shadows, regular or diffuse reflection and absorption. Above all the absorption of many terrestrial objects is considerably affected by the wavelength of the radiation so that measurement of the reflected radiation in several wavelength bands will be an additional aid for object detection (color photography, multispectral technique).

The reproduction of objects by the emitted radiation can provide information on their temperature and emissivity. The latter likewise is a function of wavelength so that measurement of emitted radiation in several wavelength regions will again facilitate object detection.

Technically we distinguish between active and passive sensors (see Fig. 4). Active sensors carry their own radiation source to "illuminate" the terrestrial object. In practical remote sensing, side-looking radar is the only active sensor that is frequently used (other frequently used active sensors are, for example, the Microwave Scatterometer and the Laser Altimeter, but these do not produce pictures). Passive sensors either record the radiation of natural sources reflected from the objects or the radiation emitted by the objects. Image-forming passive sensors include photographic cameras, thermal and multispectral scanners and passive microwave scanners.

Quantitative assessment of the interaction of the physical parameters such as "illumination", characteristic temperature, absorptivity and emissivity as well as reflection is very difficult. We shall therefore restrict ourselves to a qualitative assessment using a few examples shown in Fig. 5.

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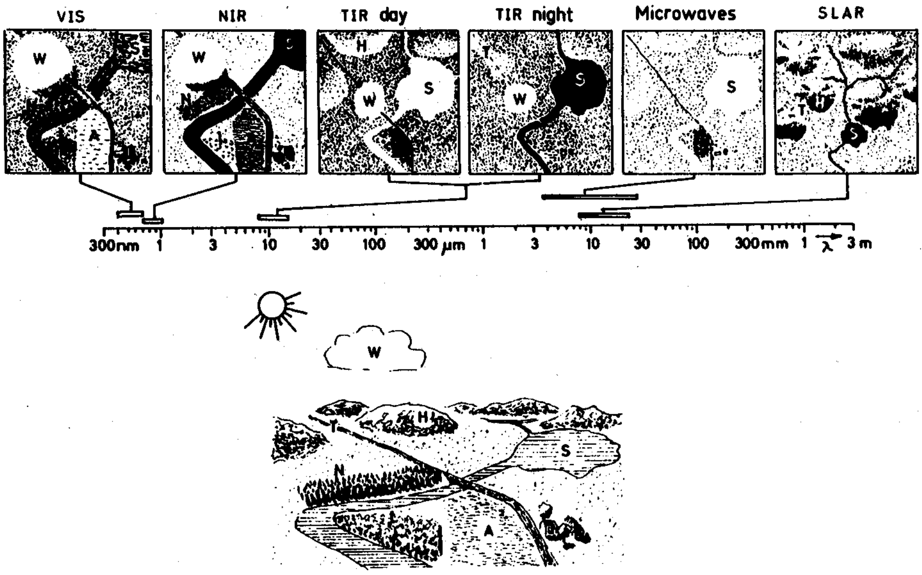

Fig. 5: Image formation in different wavelength regions.

Let the object be a landscape with a meadow, a plowed field A, deciduous forest L, conifers N, a river and a lake S, with mountains (hill H and valley T), a cloud W hovering overhead. In the visible region of the spectrum (VIS), the cloud W appears very light, the dry field A is also very light, the deciduous trees L and the conifers N dark, the meadows and the water (lake S) medium gray. A new asphalt road appears dark, and the cloud W casts a shadow that is lightened by the blue sky light.

In the near infrared region (NIR), reflected solar radiation is received like in the visible region. Meadows and deciduous trees L reflect very strongly and appear light. The conifers N appear slightly darker, but still lighter than the naked ground (field A, road, buildings). The water (lake S) absorbs very strongly and appears black. The cloud W is still light with a very pronounced shadow because it is no longer lightened by sky light.

In the thermal infrared region (TIR), the image is produced by the object's own emitted radiation. This is a function of the emissivity and the temperature of the objects. Since in this region of the spectrum most objects (except metals) have roughly identical emissivity (90 % to 100 %), image contrast is mainly due to differences in temperature. The sketches in Fig. 5 are based on the assumption that hot objects will be reproduced dark and cool objects light (so that by comparison with the sketches for the VIS and NIR regions we now have negatives). The object temperatures depend on the time of day. During the daytime, water is cold (lake is light). The black asphalt road and the field A are warm and appear dark. Vegetation has a mean temperature; there may be differences between meadows and forests. The hill H in the shade is cool and is therefore reproduced lighter. The clouds also are generally cooler than the ground. Since the clouds are moving, their shadows does not noticeably cool down the ground and therefore remains invisible. At night, temperatures are leveled and image contrast is low. Only water stands out clearly due to its higher temperature. Currents of cold air may become visible (valley T light). As regards the cloud W, it is assumed to be cooler than the ground even at night. In the microwave region, clouds are penetrated more or less unhindered by the radiation and thus remain invisible in the image. Here also, it is the radiation emitted by the objects that is recorded, the difference in relation to the thermal infrared region being that the emissivity of the objects here differs more noticeably. A passive microwave scanner will therefore record apparent temperatures which may be higher for the plowed field, for example, than for vegetation. Water reflects very strongly and appears to be very cold (lake S light) because it reflects the cold outer space.

The last sketch in Fig. 5 also refers to a picture produced by microwaves, but this time by an active sensor, namely side-looking radar (SLAR). The sensor here not only contains a receiver but also a transmitter which emits short microwave pulses. The reflected radiation of this transmitter is used for image formation instead of the radiation emitted by the objects themselves. Image contrast is primarily due to shadows which give a good relief effect. Although water reflects microwaves very well, it does so in a direction away from the sensor so that water bodies appear black in radargrams.

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This qualitative assessment was intended to illustrate the effect which the physical parameters mentioned at the beginning of this section have on image formation. In the following, we shall now turn to the technical aspects of image formation.

5. Detectors

Detectors serve to detect radiation reflected or emitted by objects. Fig. 6 shows the four physical processes on which the detectors used in image-forming sensors are based .

One possibility of detecting radiation consists in capturing the alternating electromagnetic field with an antenna and amplifying as well as rectifying the electrical oscillation so as to obtain a rectifier output voltage that is proportional to the electrical field strength (Fig. 6D). It is, of course, necessary that the amplifier and the rectifier be capable of following the high-frequency oscillations. This is why the practical application of this technique up to now is limited to frequencies up to 100 GHz, that is to radiation with wavelengths of $\lambda \geq 3$ mm, equivalent to the microwave and radiowave regions.

Radiation of higher frequency, that is shorter wavelength, can be detected by its interaction with matter. This brings us to the photographic process, photoemission and photoconduction, as well as the heating-up of matter by absorption of radiation.

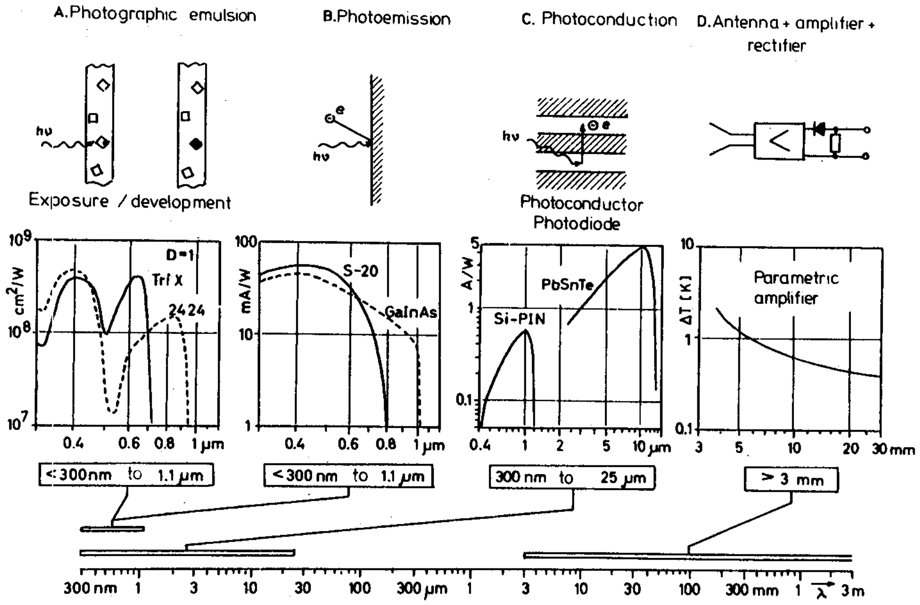

Fig. 6: Radiation detectors

The photographic emulsion contains silver-halide crystals that are embedded in a gelatine emulsion (Fig. 6A). Exposure to light forms specks of metallic silver in individual crystals. During development, the entire crystal that contains specks is then reduced to metallic silver. This metal is responsible for the image building up in the emulsion.

In the case of photoemission, electrons are ejected from a metal layer - the photocathode - by the radiation (Fig. 6B). With the aid of an electric field, these electrons can be sucked off and measured as an electric current. This effect is used in the photomultiplier detectors (which are employed, for example, for spectral bands 4, 5 and 6 of the LANDSAT multispectral scanners).

In the case of photoconduction, electrons are raised from the valence band to the conduction band of a semiconductor by the radiation (Fig. 6C). This also changes the electrical resistance of the semiconductor (photoresistive detector). If a photodiode is built up of differently doped semiconductors of this type, this may be used either as a photovoltaic cell or as a photoconductor. (Photodiodes are used as detectors for band 7 in the LANDSAT multispectral scanners.)

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The curves in Fig. 6 show the spectral sensitivity of detectors distinguished by their operating principle. Photographic emulsions and photoemission can be used up to wavelengths of about 1 µm, photoconduction up to wavelengths of approx. 20 µm. The curve for electronic amplifiers does not show sensitivity but the temperature differences ΔT that can be resolved with a microwave radiometer under standard practical conditions (radiation temperature 293 K, product of bandwidth and integration time about 5 x 10^6).

For the spectral region between 20 µm and a few millimeters there are detectors that use the heating due to absorbed radiation for detecting radiation. However, these are either of very low sensitivity or they are very inert.

6. Image-acquisition techniques

There are several image-forming techniques based on electromagnetic radiation and the detectors mentioned in the last chapter. These will be separately discussed in the following.

6.1 Photographic cameras

Photographic cameras are the most popular image-forming sensors used in remote sensing. The photographic emulsion consists of many millions of separate detectors, every single silver-halide crystal in the emulsion being a potential detector. All these detectors can be exposed simultaneously. As a result, we obtain the simplest image-acquisition technique, namely the formation of an image through a lens and simultaneous recording of all picture elements on a photographic emulsion. Fig. 7 shows the most essential components of an aerial mapping camera for the 9" x 9" negative size, using the RMK A 15/23 as an example.

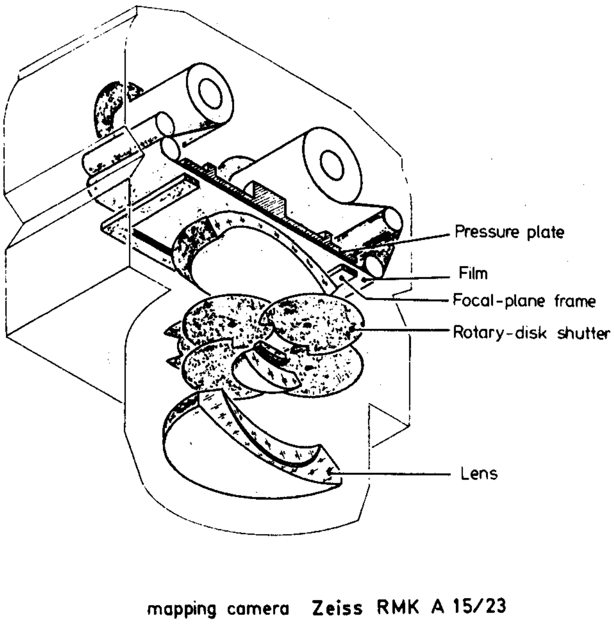

Fig. 7: Photographic camera and its major components

These components are an optical system which is composed of many separate elements to obtain high resolution, speed and freedom from distortion for a relatively wide wavelength region, followed by a shutter for speeds up to 1/1000 sec, the focal-plane frame with the pressure plate insuring perfect film flattening at the instant of exposure, and finally the film magazine holding rolls of film on spools.

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By comparison with other image-forming sensors, a photographic camera offers the advantage of simple design, very high resolution and well-defined geometry of the photographic record thus obtained, which allows very precise determination of the position of the objects recorded. The limitations of a photographic camera are due to two properties of the photo emulsion:

a) The emuslion is only sensitive to radiation of wavelengths shorter than about 1 μm and thus cannot be used for photography in the middle and thermal infrared as well as the microwave region, and
b) the relationship between the intensity of radiation and photographic density is non-linear and greatly affected by development of the emulsion; as a result, photographs make very poor base material for a quantitative evaluation regarding radiation intensity.

6.2 Scanning techniques

If we use as a detector for electromagnetic radiation either photoemission or photoconduction or a microwave antenna with an amplifier and a rectifier, we will primarily obtain electronic signals that have to be amplified and somehow transformed into an image. If we were to record all picture elements simultaneously, as in a photographic camera, we would need several million electronic amplifiers to obtain a comparable information content. This would, of course, be far too expensive. However, the problem can be overcome by not recording the picture elements simultaneously, but "scanning" them successively so that, in principle, only one detector and one amplifier are needed.

Fig. 8 shows the principle of the scanning sensor. At any time, the detector sees only a small part of the ground to be covered, the so-called instantaneous field of view. The radiation from this field produces an electric signal in the detector.

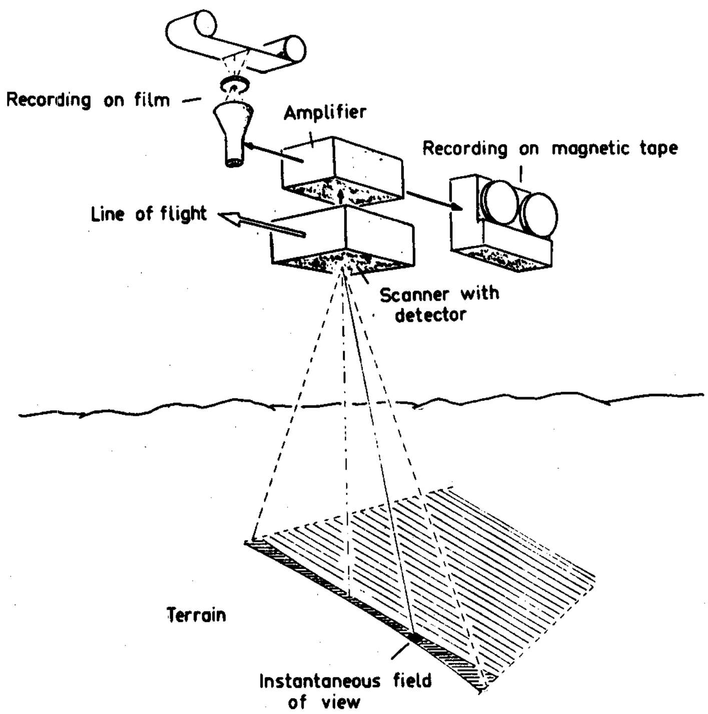

Fig. 8: Operating principle of scanning sensors

The instantaneous field of view is now shifted across the line of flight with the aid of a scanner so that the detector will successively see all the ground points on a line. Owing to the forward motion of the aircraft or the satellite carrying the sensor, a ground strip is thus scanned line by line. The electronic signal from the detector is amplified and either stored on magnetic tape or on photographic film. If the brightness of the cathode ray tube is then modulated with the detector signal and the cathode ray deflected in synchronism with the scanning ray, the target of this tube can be imaged on a slowly moving photographic film to construct a line-pattern image of the ground covered, whose density is equivalent to the radiation intensity received by the detector.

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There are several possibilities for linear deflection of the scanning ray:

6.21 Opto-mechanical scanners

A mechanically driven optical element - generally a rotating or oscillating mirror - is used to deflect the optical beam to the detector at right angles to the line of flight. Fig. 9 shows some of the most widely used systems. In each case, the axis of rotation or oscillation of the mirror is parallel to the line of flight.

A rotating mirror that is tilted 45^{0} in relation to its axis of rotation, is used, for example, in the multispectral and thermal scanners by Bendix and Daedalus. The radiation reflected by the rotating mirror is focused on the detector by means of a Newton or Cassegrain system (a concave mirror and a plane or convex mirror). The direction from which the radiation focused onto the detector is received varies with the position of the rotary mirror. Continuous rotation of the mirror insures that every revolution scans one line on the ground.

A rotary-prism mirror with four reflecting faces parallel to the axis of rotation is used in the thermal scanners by Texas Instruments. Two reflecting surfaces are always used simultaneously. The radiation reflected by these surfaces is transmitted via additional mirrors to a concave mirror at the focus of which the detector is located. Four ground lines are thus scanned per revolution of the rotary mirror.

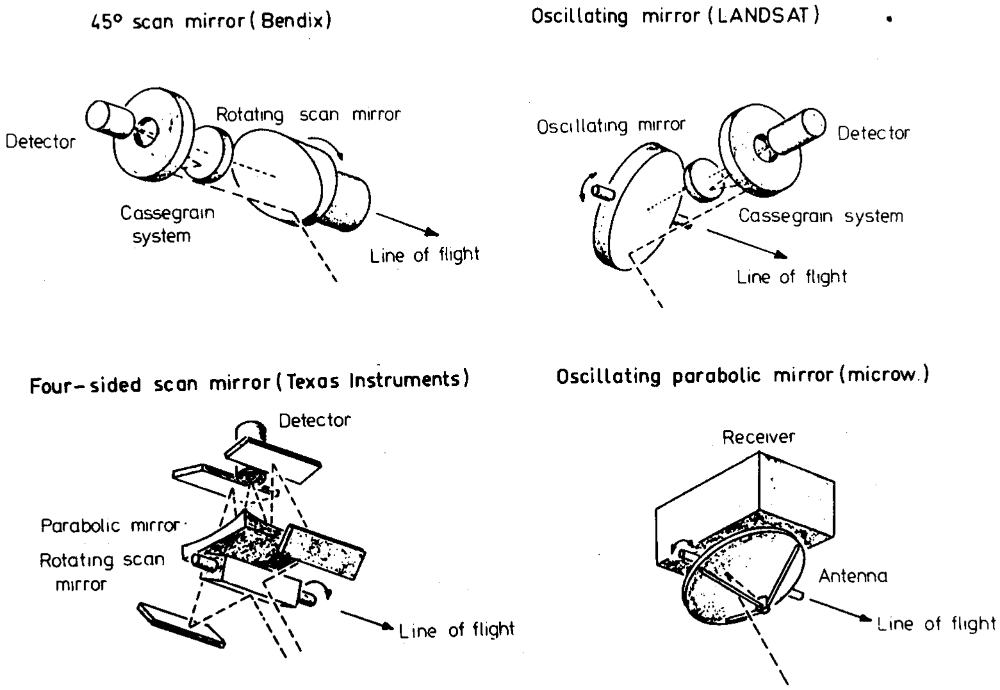


Fig. 9: Opto-mechanical scanners

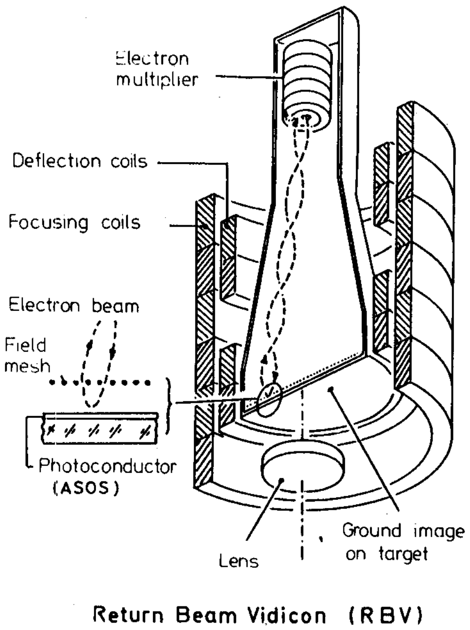
An oscillating mirror is used, for example, in the multispectral scanners of the LANDSAT satellites. The radiation reflected by the mirror is focused via a Cassegrain system. In Fig. 9, a single detector is located at the focus. In the LANDSAT multispectral scanners, the ends of glass fibres are located at the focus of the Cassegrain system, which transmit the radiation to a total of 24 detectors (six detectors for each of the four spectral bands).

Oscillatoring mirrors may also be used in image-forming microwave sensors. In this case, they are of the parabolic type and direct the radiation onto the antenna horn.

6.22 Electronic scanners

Opto-mechanical scanners focus only a very small portion of the object on the detector, the actual scanning motion being obtained by rapid displacement of the object image on the detector. By contrast, a large section of the object is imaged on the detector in the sensors that are here termed "electronic detectors". The radiation generates a distribution of electrical voltage or charge on the detector, which is electronically scanned.

Fig. 10 shows the principle of two such scanners. The Return Beam Vidicon is used, for instance, in the second sensor of the LANDSAT satellites. This is a high-resolution and highly sensitive tube similar to a TV camera tube. An image of the ground is formed on the target of the tube by an objective. The tube carries a light-sensitive semiconductor layer (ASOS = antimonide sulfide oxysulfide) that is electrically charged. The incident radiation makes this layer conductive and eliminates the electrical charge, acting most quickly on heavily exposed points. The result is a distribution of charge and thus of potential, which is equivalent to an optical image. Since the layer is highly resistive, the charge image is preserved for a certain period of time. During this period, the electron beam scans the image line by line. The dark points, at which the rear of the detector layer still has a strong negative charge, reflect many electrons, while light points in the image reflect only a few. The reflected electrons are transmitted to an electrode where they eject additional electrons. These secondary electrons are further amplified at several dynodes and finally generate the electronic video signal at the anode of the photomultiplier tube. After amplification, this signal can be stored, for instance on magnetic tape. The charge image has to be erased after scanning. This is done by uniform exposure of the entire layer. Next, the layer is again charged with the aid of the electron beam and thus ready for another scanning cycle. Although the semiconductor layer is a homogeneous detector, its high electrical resistance makes it act like a multitude of individual detectors. The layer has a resolution of about 100 line pairs per millimeter.



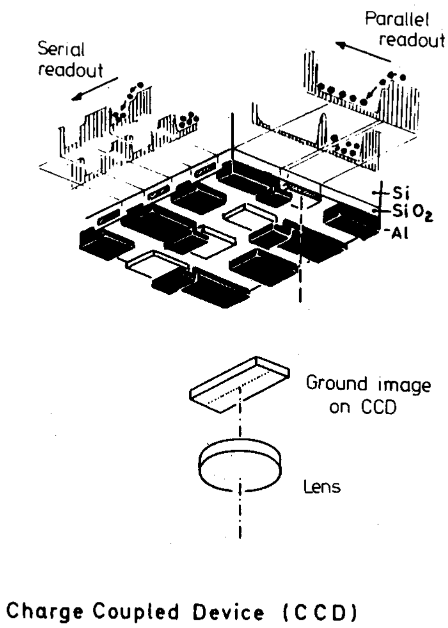


Fig. 10: Electronic scanners

So-called charge-coupled devices (CCD) are composed of genuine discrete detectors. Fig. 10 gives a diagrammatic representation of the design and operation of a CCD line scanner. A line of detectors is contained on a silicon chip. The detectors consist of capacitors whose one electrode is n-type silicon. The incident radiation liberates electrons in the silicon that are retained in the capacitors. A pair of additional, unexposed capacitors is located beside each of the aforementioned detectors. If the sign of the voltage applied is now changed, the resulting charges will be transferred to one of these previously empty capacitors, a process that is simultaneous for the entire line of detectors. Scanning proper of the charge image now available in the storage capacitors is made serially via the line of storage capacitors. The charges are shifted along this line by periodic variation of the voltage applied and read out as in a shift register. The CCD arrays presently available contain up to 1728 detectors on a length of 22.4 mm, that is with a resolution of approx. 40 line pairs/mm.

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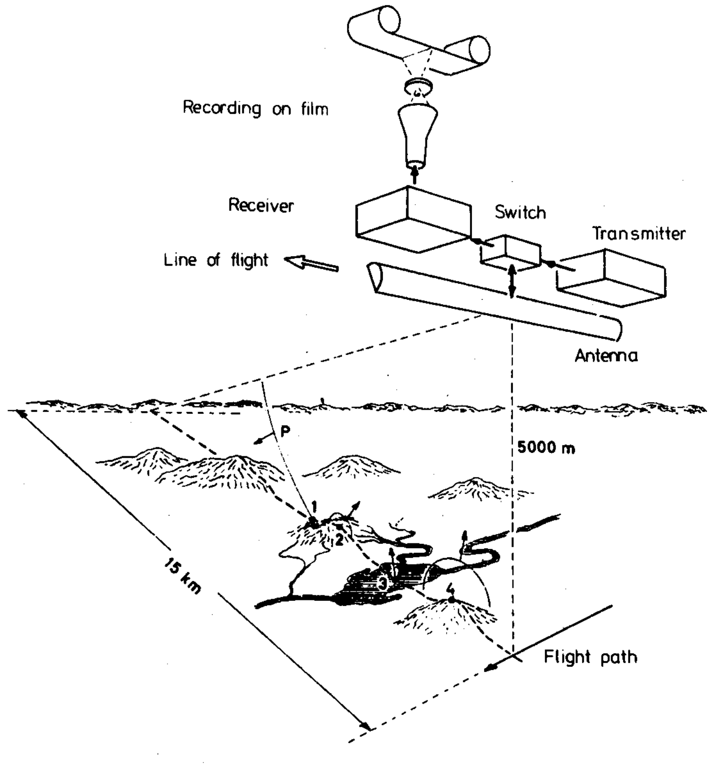
6.23 Travel-time scanners (side-looking radar)

In the case of side-looking radar, the finite speed of propagation of electromagnetic radiation is used for scanning the terrain. Fig. 11 shows the principle of Real Aperture Side Looking Airborne Radar (SLAR). This is an active sensor which carries its own radiation source - a microwave transmitter - and uses the radiation reflected by the ground for image formation. The transmitter generates a brief microwave pulse, which is emitted by the antenna. Then the antenna is switched over to the receiver. In the meantime, the pulse emitted travels towards the ground surface. In Fig. 11, the pulse front P has just reached the surface at point 1. The long antenna sharply focuses the emitted radiation in the direction of flight so that only a relatively narrow line at right angles to the line of flight is irradiated on the ground. Point 2 was reached earlier by the pulse front than point 1; the radiation reflected there travels upwards, and part of it will again reach the antenna after a certain delay. Point 3 on a water body was reached even earlier, but the smooth water surface reflects the radiation regularly so that no part of it returns to the antenna. This is why water appears black in radargrams. Point 4 also was reached earlier by the pulse front, and the radiation reflected there will reach the antenna first. The reflected microwave radiation received by the antenna is then transmitted to the receiver, amplified and rectified and can be used as a signal to modulate the intensity of the electron beam of a cathode ray tube. For each of the microwave pulses emitted, an image line is produced on the target of the tube, in which the brightness is a function of the intensity and image geometry one of the deflection speed of the electron beam and the travel time of the reflected radiation. The image line can be successively recorded on a continuously moving film. At a flying height of 5000 m, the width of the ground strip scanned is about 15 km. The resolution in the direction of the lines, that is at right angles to the direction of flight, is determined by the duration of the transmitter pulse; in the direction of flight it is determined by the length of the antenna. In either direction resolutions of about 25 m are attained, for which the antenna must be about 4 m long (Westinghouse AN/APQ-97, K_a-band, $\lambda \approx 10$ mm).



Side-looking radar

Fig. 11: Real Aperture Side Looking Radar (SLAR)

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Shorter antennas will do for Synthetic Aperture Radar (SAR) and will even give higher resolution (15 m at a flying height of 15 000 m with Goodyear APQ-102, X-band, λ = 30 mm). Here also, scanning across the line of flight is made via travel-time analysis. Unlike the real-aperture radar, the image in the direction of flight is not obtained by focusing the radiation with the aid of an antenna, but using the frequency shift of the reflected radiation. The shift is due to the Doppler effect and the motion of the aircraft. As in the real-aperture radar, the received signals are recorded by lines on photographic film. However, the intensity of the electron beam of the tube is not modulated directly with the signal but by superimposing the transmitter frequency on the reflected signal. Fig. 12 illustrates the operation of synthetic-aperture radar for a single point object. As the aircraft passes the object, the frequency of the reflected radiation is initially higher - and after the aircraft has passed, lower - than the transmitted frequency. The frequency differential is recorded on the film in proper phase relation and gives a pattern of varying spatial frequency. This pattern covers 1000 or more image lines, equivalent to a flight distance of several hundred meters. This flight distance is the synthetic aperture which has given the method its name.

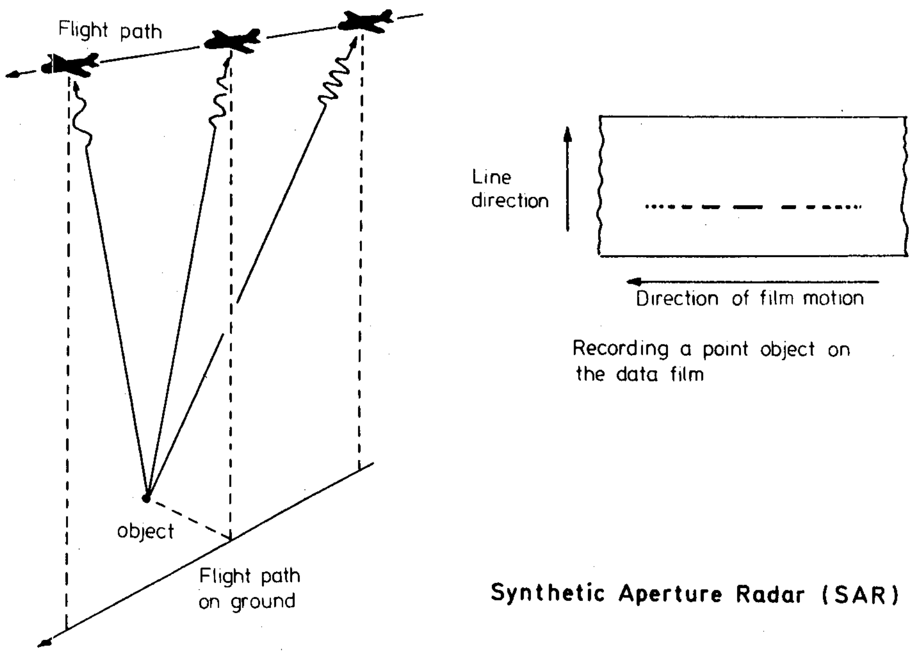

Fig. 12: Operating principle of Synthetic Aperture Radar

In the case of an extensive object such as the surface of the earth, which is made up of a multitude of separate point objects, the image patterns of all points located at the same distance from the flight path will be superimposed. The primary image recorded on the "data film" is not an object image in the normal sense, but contains the information in a form similar to a hologram. A true image of the area covered can be obtained from the data film by means of coherent optics, similar to the techniques used for reconstructing images from holograms.

6.24 Phased arrays

For microwave scanners we not only have the possibility of opto-mechanical scanning with a moving concave mirror (see item 6.21) but also one of linear scanning without mechanically driven elements with the aid of a phased array.

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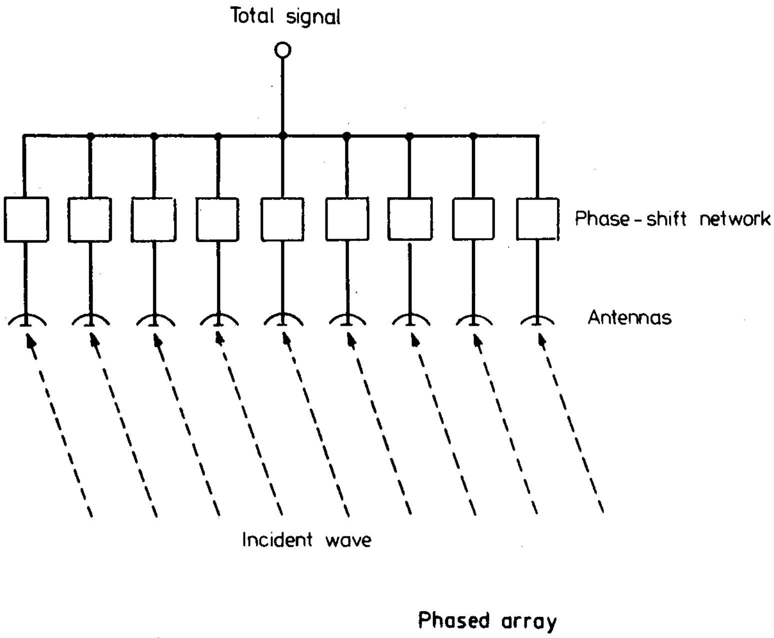

Fig. 13: Operating system of phased array

Such an array consists of a multitude of regularly disposed antennas and the corresponding electronic circuit with which the phase of the received waves can be influenced. Fig. 13 is a diagrammatic representation of a one-dimensional phased array. If the phases of the waves received by the different antennas are suitably delayed and if then all signals are added, they will cancel out except for those of a wave from a certain direction. Electronic control of the phase-shift networks allows the direction sensitivity of the array of antennas to be controlled to obtain linear scanning without having to move the array mechanically.

A passive microwave scanner working on this principle is used, for example, in the NIMBUS-5 satellite (Electrically Scanning Microwave Radiometer ESMR, wavelength region K-band, λ = 15.5 mm, dimensions of array 83 cm x 85 cm, geometrical resolution 1.4^o, scan angle $\pm 50^o$).

7. Geometric and intensity resolution

The preceding items 5 and 6 have dealt with detectors of electromagnetic radiation and image-acquisition techniques using these detectors. However, hardly any mention has been made of the limits of the different methods that are given by error sources. Pushing back these limits by reducing errors is the major problem in designing sensors and has a decisive effect on the quality of the final product. We shall therefore devote the following two sections to a brief discussion of such error sources. While this section will deal with statistical error sources, item 8 will be devoted to systematic ones.

Statistic errors are called noise. An important cause of statistic errors is the quantum nature of electromagnetic waves and electric charges. For a statistical current of identical events (current of radiation or charge quanta), the variance σ^2 of the number of events measured in the period τ is proportional to the mean number of events $\bar{n}$:

$$\sigma^2 \propto \bar{n}.$$

It follows from this that the mean current fluctuation, namely noise, is

$$\emptyset_R = \frac{\sqrt{\sigma^2}}{\tau} \propto \frac{\sqrt{\bar{n}}}{\tau} = \sqrt{\emptyset/\tau}$$

and if we call the mean current $\emptyset = \bar{n}/\tau$ the signal, we obtain for the signal-to-noise ratio

$$S/R = \emptyset/\emptyset_R \propto \sqrt{\emptyset \cdot \tau}$$

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If the detector has a quantum efficiency of $\eta < 1$, the number $\bar{n}$ of detected events (radiation quanta) is smaller by the factor η, and the signal-to-noise ratio is thus reduced to

$$S/R \propto \sqrt{\eta \cdot \phi \cdot \tau}$$

The signal-to-noise ratio is the number of resolvable intensity or gray levels, because intensity differences smaller than the mean fluctuation of intensity cannot be detected. Consequently, to obtain high intensity resolution, we need

high quantum efficiency η of the detector,
high radiant flux ϕ detected, and
long measurement time τ .

The quantum efficiency of detectors cannot be influenced by either the manufacturer or the equipment user. Coverage of a high radiant flux ϕ means optical systems of high aperture, that is large and heavy sensors. Long measurement time per picture element, however, means reduction of recording speed, that is either a reduction of the object area recorded per unit of time or a reduction of the number of picture elements recorded, which is equivalent to a reduction of geometrical resolution.

In other words, geometrical and intensity resolution are incompatible for a detector of given quality and a sensor of given size. A limit is thus reached that can only be pushed back by using several detectors instead of a single one. In the case of photographic cameras with the many million individual detectors of the photographic emulsion, this solution has been used for a long time already. This is why the image quality of photographic cameras is still better than that of all other sensors. But even line scanners are increasingly using several detectors and scanning the object in line groups instead of line by line. An example is the LANDSAT multispectral scanners in which six lines are simultaneously scanned in every spectral band.

Up to this point, we have discussed only the noise caused by the quantum nature of radiation. However, all sensors are affected by additional statistical error sources. In the photographic emulsion, this is the statistical distribution of position and size of the silver-halide crystals and the "quantization noise" produced by the fact that a developed crystal can only adopt one of two gray levels: black or white. These two effects together result in the grain structure of the photographic image.

In electronic detectors, additional error sources are the dark-current noise of the detector and the thermal noise in the amplifiers. These can be largely eliminated by cooling to low temperatures. Cooling is particularly important with detectors for the thermal infrared region. Here, the dark current of the uncooled detector is large because even if there is no signal radiation, the detector will still see the thermal radiation emitted by itself and its surroundings. Cooling the detector and the aperture limiting the field of view can considerably improve the signal-to-noise ratio.

Finally, fluctuations with time of object illumination and detector sensitivity are other important error sources that are not predictable and thus of a statistical nature. The errors thus produced can be reduced with the aid of calibration radiators.

8. Quantitative image evaluation

The images obtained with the aid of sensors are evaluated in two different ways. The intensity distribution, that is the gray levels of the images, allows a detection or classification of objects. A geometrical evaluation of the images allows determination of the position of detected objects.

It is obvious that quantitative image evaluation is possible only within the limits given by statistical errors. In addition, however, there are systematic errors. In principle, these can always be taken into account, although this is more or less expensive. The following table lists the most important sources of systematic errors and the difficulty of taking them into account.

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	Frame camera		Line scanner	
EXTERNAL ERROR SOURCES	Monoband	Multiband	Mono-spectral	Multi-spectral
Atmospheric background radiation	•	●	•	●
Object shadows	•	●	•	●
Angular dependence of reflection	•	●	•	●
SENSOR-RELATED ERRORS				
Distortion	+	+	**+**	**+**
Sensor motion	+	+	**+**	**+**
Irregular sensitivity	●	●		•

● Intensity-measurement error
+ Image-geometry error

The sensors listed in the table are the (photographic) frame camera and the linear scanners that are primarily based on electronic detectors. These sensors may either work in only one spectral band or simultaneously record images in several spectral bands (multiband or multispectral technique). In this method, the spectral reflection properties of objects can be used as an aid in object recognition. Since in this case it is generally a question of measuring only minor intensity differences, the multispectral techniques are particularly susceptible to errors of quantitative intensity measurement.

External errors are atmospheric background radiation (scattered radiation, such as sky light and radiation emitted by the atmosphere), whose intensity is a function of the thickness of the air layer, that is of angular field, furthermore object shadows (in the visible region, object parts in the shade are differently illuminated by the sky light than object parts irradiated by the sun) as well as the angular dependence of object reflection.

Sensor-related errors are distortion, which may be very large in line-scan pictures, furthermore image distortion due to sensor motion during recording (allowance for these distortions can be made easily in frame-camera photography, but only with difficulty in line-scan pictures) and finally, irregularities of detector sensitivity. In line scanners using several detectors, such irregularities can be taken into account relatively easily. In photographic cameras, these irregularities are produced by lens vignetting, uneven film processing as well as poor reproducibility of photographic emulsions and development. In quantitative intensity measurement, irregularities due to the film and its development can be taken into account only with difficulty.

The table shows that photographic frame cameras are preferable for geometric image evaluation, while sensors with electronic detectors are better suited for intensity measurement in the pictures. An optimum solution for quantitative image evaluation would be a camera with so many simultaneously exposed electronic detectors that the resolution of a photographic camera of identical angular field is reached. However, a sensor of this type is not yet available, and neither will it become technically feasible at a reasonable price in the foreseeable future.

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Abstract

The paper gives an outline of the physical and technical operation of image-forming sensors using electromagnetic radiation in the wavelength region from 300 nm to approx. 1 m. These include photographic cameras, thermal and multispectral scanners, microwave scanners and side-looking radar.

A brief description of atmospheric windows, radiation sources and object properties affecting image content is followed by a discussion of detectors of electromagnetic radiation and of image techniques (aerial cameras, optomechanical scanners, electronic scanners, travel-time and phase scanners). Finally, the basic problem of all image-forming sensors, namely a compromise between high geometric resolution and high intensity resolution (signal-to-noise ratio) as well as the problems of quantitative image evaluation (geometry and intensity measurement) are mentioned briefly).

Sensoren für die Fernerkundung

Zusammenfassung

Es wird ein Überblick gegeben über die physikalisch-technische Funktion von bilderzeugenden Sensoren, die mit elektromagnetischer Strahlung im Wellenlängenbereich von 300 nm bis etwa 1 m arbeiten. Hierzu gehören die photographische Kamera, die Thermal- und Multispektral-Abtaster, die Mikrowellen-Abtaster und das Seitwärtsradar.

Zunächst werden die atmosphärischen Fenster, die Strahlungsquellen und die für die Bildinformation maßgeblichen Objekteigenschaften kurz dargestellt. Im Hauptteil des Vortrages werden die Detektoren für elektromagnetische Strahlung und die Verfahren der Bildaufnahme diskutiert (Luftbildkamera, optisch-mechanische Abtaster, elektronische Abtaster, Laufzeit- und Phasen-Abtaster). Das für alle bilderzeugenden Sensoren grundlegende Problem des Kompromisses zwischen hoher geometrischer Auflösung und hoher Intensitätsauflösung (Signal:Rausch-Verhältnis), sowie die Probleme der quantitativen Bildauswertung (Geometrie und Intensitätsmessung) werden am Schluß kurz angesprochen.

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Capteurs pour la télédétection

Résumé

L'exposé donne un apercu des fonctions physico-techniques que remplissent les capteurs de télédétection travaillant dans le spectre des ondes électromagnétiques, de 300 nm à environ 1 m. Cette catégorie de capteurs comprend les caméras photographiques, les scanners thermiques, les scanners multispectraux, les scanners centimétriques et le radar aéroporté à antenne latérale.

L'exposé examine tout d'abord rapidement les fenêtres atmosphériques, les sources de rayonnement et les caractéristiques des objets au sol, importantes pour le recueil des informations par les capteurs. Il traite ensuite en détail les détecteurs pour rayonnement électromagnétique (caméras pour photographies aériennes, capteurs optomécaniques, capteurs electroniques, capteurs à ondes progressives et à phase) et les méthodes de prise de vues. Pour terminer, il aborde le problème fondamental qui se pose pour tous les capteurs, à savoir le compromis entre une haute résolution géométrique et une haute résolution d'intensité (rapport signal/bruit), ainsi que les problèmes de l'interprétation quantitative des images (géométrie et mesure d'intensité).

Sensores para la exploración remota

Resumen

Se da una visión de conjunto sobre la función fisicotécnica de sensores generadores de imágenes que trabajan con radiación electromagnética en el margen de ondas desde 300 nm hasta aprox. 1 m. Se cuentan entre estos las cámaras fotográficas, los exploradores térmicos y multiespectrales, los exploradores de microondas y el radar lateral.

Primeramente, se explican de forma breve las ventanas atmosféricas, las caracteristicas de los objetos decisivas para la información de la imagen. La parte principal de la conferencia trata de los detectores para radiación electromagnética y de los métodos de registro (cámara aérea, exploradores óptico-mecánicos, exploradores electrónicos, exploradores de fase y tiempo de propagación), El problema fundamental de todos los sensores generadores de imágenes de un compromiso entre alta resolución geométrica y alta resolución de intensidad (relación señal : ruido), asi como los problemas de la restitución cuantitativa (geometría y medición de intensidad) se discutirán brevemente al final.

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