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SENSORS AND METHODS FOR WEATHER-INDEPENDENT REMOTE SENSING WITH MICROWAVES

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16. Abstract

Sensors and methods of radar and microwave radiometry which operate in the millimeter wave range are discussed. A description is given of the properties of electromagnetic waves, and the resolution capacity and measurement accuracy of sensor systems. Future possibilities are presented.

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ANNOTATION

In the field of Earth sensing, the use of microwave sensors and methods are becoming more important especially because of their weather-independence. At the Institute for High Frequency Technology and in the entire DFVLR, there has been a tradition in the areas of radar and microwave radiometry. The Institute for High Frequency Techniques is substantially involved in the development and investigation of sensors and methods for remote sensing using microwaves. Professor Ulbricht who was Director of the present High Frequency Technique Institute up to 1970 (at the time the Institute for Aviation Radio and Microwaves) and the member of the DVL management, became 75 on May 12, 1980. Some of the sensors and sending methods used today at the institude are due to his initiative and direction.

SENSORS AND METHODS FOR WEATHER-INDEPENDENT REMOTE SENSING WITH MICROWAVES /34*

W. Keydel,** Dr. rer. nat.

Remote sensing is the determination of the properties, state and behavior of objects and their surroundings using active and passive remote measurement methods. Here by remote measurements we mean that the measurement, that is, the information exchanged between a sensor and an object, is carried out without any contact. The distances between the measurement probe and the object can vary between very short distances and astronomical distances.

Basically, both electromagnetic wave and acoustic waves and matter are suitable (that is, particle radiation) to transfer information between the object and the sensor. In the following we will discuss sensors and methods which use electromagnetic waves as information carriers. The usable spectrum of electromagnetic waves extends from the long wave range with a wavelength of several 100 km, to the shortwave gamma radiation with wavelengths on the order of 10^{-15} cm and less. Sensors and methods exist for remote sensing in all wavelength ranges. Gamma radiation spectroscopy with scintillation counters is used to research nucleons and their energy levels in the atomic nucleus. In the visible range of the spectrum, at wavelengths between $4 \cdot 10^{-9}$ cm and $8 \cdot 10^{-9}$ cm, cameras, telescopes and our eyes are examples of sensors. In the infrared, radiometers and lasers are used as remote sensing instruments.

In the following we will discuss sensors and methods of radar and microwave radiometry which operate in the millimeter wave range. This range extends from wavelengths on the order of 1 m to 1 mm. The wavelength and frequency are reciprocal quantities. Therefore, this wavelength range corresponds to a frequency

*Numbers in margin indicate pagination of foreign text.

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range between about 300 MHz and 300 GHz.

Properties of electromagnetic waves

Electromagnetic waves are characterized by their amplitude, phase, frequency and polarization. They have the property of propagating in a straightline way with a finite velocity which depends on the properties of the media (in a vacuum, the speed of light is $3 \cdot 10^8$ m s^{-1}). They can interfere, that is, using so-called correct phase superposition of several wave trains, one can bring about amplification of the wave or extinction. Electromagnetic waves can scatter. This means that opticals in their propagation paths will not produce any sharp shadows. Instead, parts of the wave will reach the shadow region from the geometric shadow boundary. The wave is refracted around the optical.

All of these characteristics and properties are the reason why the electromagnetic waves are very well suited as information carriers for remote sensing. The finite and usually known propagation speed can be used over a measurement of a running time period to determine the distance. By measuring frequency and its change, speed measurements can be performed. This can also be used to improve resolution and for recognizing the structure of the object. Amplitude measurements can give information about the size, structure and type of objects and their position from which the wave emanates. Phase measurements are used to determine the location by using angle measurements. Knowledge about the polarization of the wave and its change can give information about the structure of the object. This is especially true for electromagnetic waves of all spectral regions.

For remote sensing of the Earth and for determining and observing objects as targets on it, such as growth, surface structure, urbanization, land vehicles, aircraft and ships, two spectral regions are used mostly today. These are the microwave range

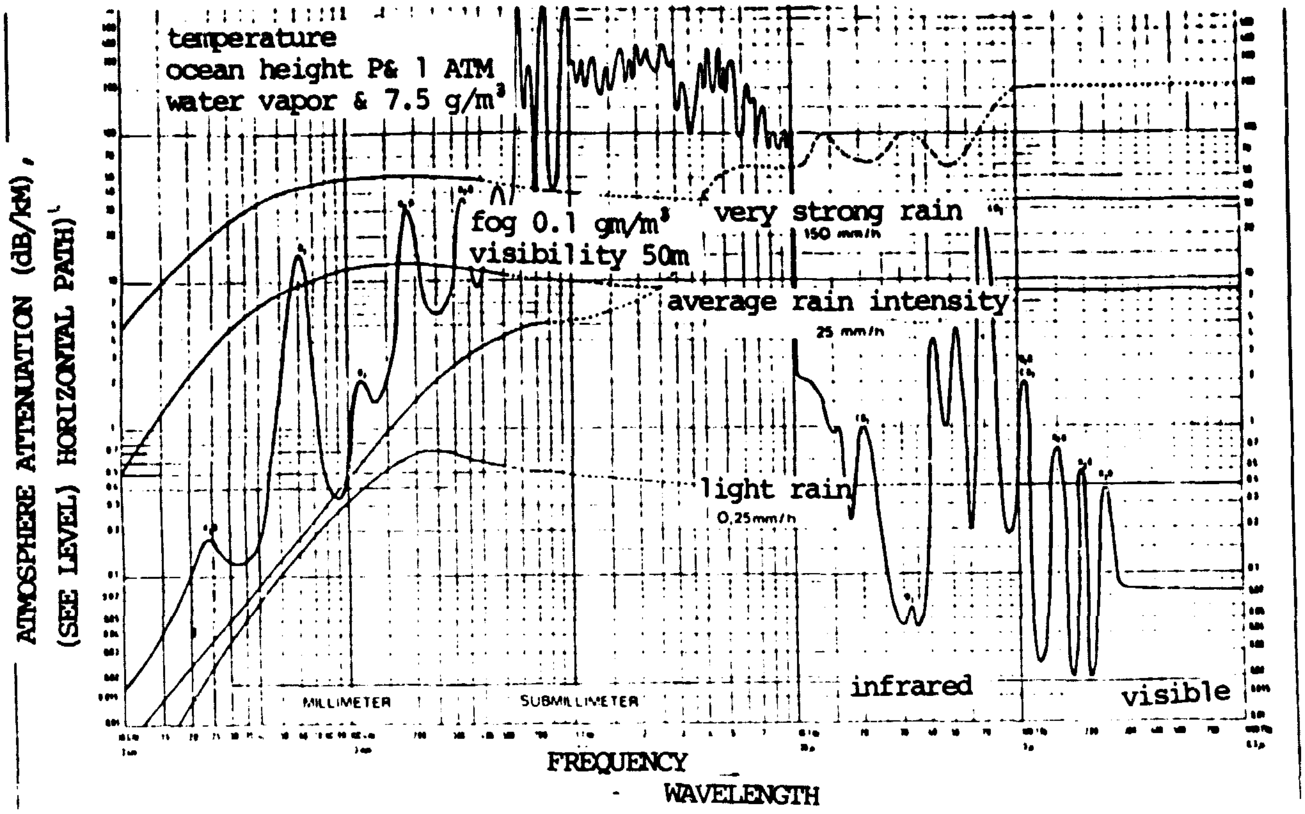

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Figure 1. Damping by atmosphere gases, rain and fog.

(m to mm waves) and a so-called optical range which extends from the thermal infrared over the visible range to the ultraviolet radiation and encompasses a wavelength range between about 10^{-1} to 10^{-5} mm.

The selection of the wavelengths to be used, that is the frequency range, depends essentially on the deployment conditions, the environment and the targets being researched. In general, one has to reach a compromise between various factors, such as, for example, resolution, range, test duration, observation time, amount of data and space available for setting up and transporting the sensor. Advantages and disadvantages are inherent for each of the wavelength ranges.

The microwave range has the following advantages over the optical range:

Microwaves experience a smaller damping by the atmosphere than do optical waves, especially for rain and fog. Figure 1 shows the damping on a logarithmic scale as a function of wavelength and frequency. The electromagnetic waves per km of propagation path in atmosphere under normal conditions and for rain or fog are shown. The superiority of the microwaves compared with optical wavelengths is especially true for fog conditions where the difference in the propagation damping for a visible range of 50 m is more than 100 dB per km. This corresponds to a factor of 10^{10}, i.e., for fog and clouds, this is almost an impenetrable obstacle in the optical range. For microwaves, there is almost no influence. It is especially true for centimeter and decimeter waves. /35

Microwaves are capable of penetrating into a surface. The penetration depth of an electromagnetic wave in a layer subject to radiation is directly proportional to the square root of the wavelength for wide regions of the Earth's surface. This is why, for example, the penetration depth of a 3 cm wavelength for certain surfaces is 100 times greater than if a 3μm ($3 \cdot 10^{-4}$ cm) wave is used. This is the so-called middle infrared range. In particular, it is easier to penetrate growth, loose ground properties, snow and ice using microwaves.

This advantage is offset by the disadvantage that microwave sensors in general have a smaller angular resolution capacity than do optical sensors. Also, the complexity in the microwave range is substantially greater, if one wishes to achieve an image resolution which is comparable to that of the optical range.

Resolution capacity and measurement accuracy of sensor systems

The concept of resolution capacity is used in many ways in physics and technology. Various definitions for different regions exist. In radar technology, one distinguishes between distance resolution capacity, velocity resolution capacity, angular resolution capacity and the so-called radiometric resolution capacity of images. In radiometry, one also speaks of temperature resolution.

By the term resolution capacity we mean the smallest dimension which can still be distinguished. In other words, the resolution capacity is a measure for differentiation of two objects which differ in terms of measured variables, such as distance, speed, azimuth position with respect to the sensor, brightness or temperature.

For all sensors which record electromagnetic waves, the angular resolution is very important. This is a minimum angle under which two objects, details for measured points, can lie so that they still can be distinguished as two separate measurement objects by the sensor. There exists a physical lower limit for this which is independent of the evaluation and depends only on the aperture of the sensor, the size of the optics, and this is a consequence of the refraction and interference of electromagnetic waves. In all frequency ranges of the spectrum, the lower resolution boundary for the imaging system is given by the quotient of the wavelength and the aperture. Essentially, the aperture is the diameter of the objective or the antenna. In the microwave range, the antenna takes on the same role as the objective plate in optical systems or as the eye in humans. Therefore, the antenna is one key component in the remote sensing using microwave sensors.

The refraction at the end of an objective, the so-called pupil, is responsible for the fact that when a plane wave enters in the image plane, not only is a focus point created, but there is a brightness variation with a principal maximum and several side maxima which are separated by dark ringed zones from one another.

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Two signals from different objects, which create such a diffraction image in the image plane of an optical system, will be called separable and resolve if the principal maximum of one of them falls within the first minimum of the second one. This is the Helmholtz definition of resolution capacity.

It becomes understandable why in astronomy the observation instruments (for example, lenses and mirrors) are made as large as possible. This is because the performance limit of optical systems is only determined by the boundary of the incoming light bundle and not by the special lens or mirrors designed.

The mirror of the Mount Palomar Observatory has a diameter of 5 meters which corresponds to an angular resolution of 0.01 seconds of arc for a light wavelength of $5 \cdot 10^{-4}$ mm. Two fixed stars having this separation can still be distinguished. For a lens diameter of 50 meters, the resolution is 10 times smaller, it is 0.1 seconds of arc. With objective diameters of 5 cm (which are commercially available), one can achieve a resolution of 1 second of arc.

The resolution capacity of the human eye at an average light-wave length of $5 \cdot 10^{-4}$ mm and a pupil diameter between 1 mm and 8 mm and which depends on brightness (here we assume 5 mm) is one minute of arc on the average. In order to achieve the same resolution in the microwave range, extremely large apertures are required. For a wavelength of 10 cm, an antenna having a diameter of about 344 m is required. For 1 cm wavelengths, we still require 34 meters in order to achieve the same resolution of 1 minute of arc. This example clearly shows the problem of microwave methods for remote sensing of the Earth and the large disadvantages which the long wave microwaves have compared with the short optical waves. These disadvantages, however, are offset by the mentioned advantages of all weather capacity and the large penetration depth. Nevertheless, in the decimeter wavelength range and the centimeter wavelength range with antennas which have a diameter of 3.4 m, one can achieve a resolution of about 2° for 10 cm wavelengths and about 12 minutes of arc for 1 cm wavelength. With 34 cm diameter antennas, one can still achieve 20° at 10 cm wavelengths or 2° at 1 cm wavelength. From this we can see the importance of the antenna aperture on the resolution of a microwave sensor.

However, we clearly have to point out here that the concept of measurement accuracy, also angular measurement accuracy, is not identical with the resolution capacity. The concept of measurement accuracy is oriented only with respect to a single target. The angular measurement accuracy of a microwave sensor is proportional to the ratio of the aperture and the wavelength, but at the same time it is also proportional to the signal-noise power (S/N). This means that the measurement accuracy can be improved by improving the S/N. For example, this can be achieved by high performance amplifiers with low noise (that is n) or by increasing the observation time (larger S by summing) or by increasing the antenna size. When the antenna diameter is doubled, one obtains four times the area. Then from the power reaching the antenna (power per unit area), one can draw off four times the power. It follows from this that the antenna size is important not only for resolution, but also for measurement accuracy and power level, that is the power output of a microwave sensor.

Principles of microwave sensors and methods

A microwave sensor has the task of collecting information objects. It records microwave radiation which reaches the sensor from the object and evaluates its information content. One distinguishes between active and passive methods depending on whether the radiation power to be detected is produced by the source, or whether the radiation is detected which is radiated by any body without the influence of the observer. In the first case, one calls this radar, in the second case we call it microwave radiometry.

The word radar is an artificial word from the English derived from radio detection and ranging. By this we mean equipment as well as methods for the detection, position determination and identification of objects with electromagnetic waves. The German names for radar include "radio measurement methods" or "radio measurement units". Radar operates using the echo principle

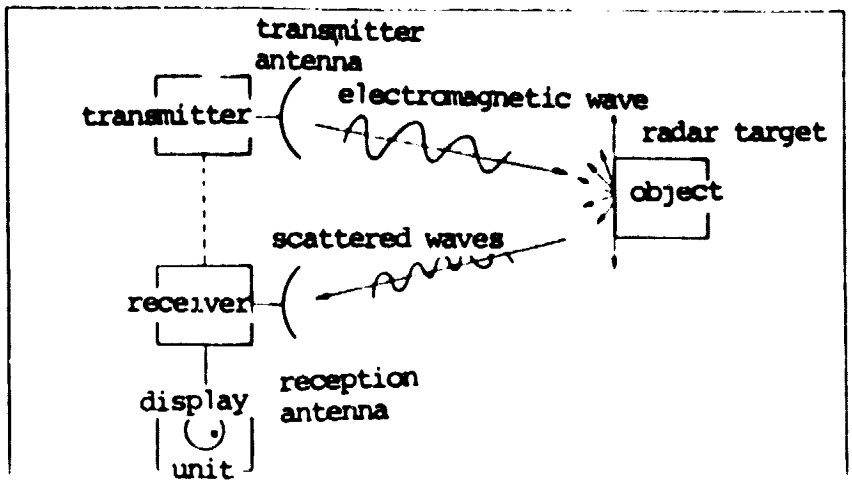

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Figure 2. Principle of the radar.

according to Figure 2. A transmitter radiates electromagnetic waves through an antenna which are then scattered in free space and are scattered by inhomogeneities or objects, the radar targets. Part of the scattered waves then reach the receiver. The sensor itself consists of the reception antenna (the eye of the unit) for recording the scattered power, a receiver (the brain of the unit) for processing the recorded signals and a display unit for presenting the measured results. The connection between the transmission part and the receiving part can be close or far. There are methods where the transmitter and the receiver are separated in space, so-called bistatic methods. Very often we have the case where the same antenna is used for transmission and receiving, and there is a close information connection between the transmitter and the receiver. In general, the received wave has different characteristic properties, such as amplitude, phase, frequency and polarization compared with the transmitted wave. From these changes one then obtains the basic information about the targets.

In general, the radar unit poses the following questions to its surroundings:

- are targets available?
- how many targets are available?

	E-SLAR	2-FS-scatter-ometer	MRSE-SAR planned for con-struction at Dornier	MRSE-2-FS scattero-meter
radar type	pulse radar	pulse Doppler radar	SAR	pulse Doppler radar
frequency	9.6 GHz	1260 MHz-1320 Mz variable	9.65 GHz	9.62...9.65 GHz
average transmission power	350 mW	1mW-50W	240 W	120W
peak power	7 kW	50W	3.3kW	3.4 kW
pulse duration	50 ns	33 ns - 8.5 μs variable	8 μs	2 μs
pulse repetition frequency	1000 Hz	25 kHz - 200 kHz variable	10 kZ	10 kHz
antenna dimensions	430 cm x 20 cm	1 m dia-meter	200 cm x 100 cm	200 cm x 100 cm
half widths	0.[illegible]° x 45°	13°	1.1° x 2.2°	1.1° x 2.2°
area resolution	15m x 15m for 1 km flight altitude. Inclination angle 20°-70°	320m x 462m 1 km flight altitude inclin-ation angle 45°	25m x 25m 250 km flight altitude. Inclination angle 45°	7.5 km x 21 km 250 km flight altitude. In-clination angle 45°
application	flights, cartography of the Earth sur-face	static applica-tions and flight, ocean sur-face, ocean state and flows	space shuttle, Earth surface, land and ocean	Space shuttle, ocean surface, ocean state and flows

TABLE 1. Radar equipment (MRSE) for Earth reconnaissance available and planned at the High Frequency Technology Institute of the DFVLR.

- where are the targets?
- which properties do the targets have?

According to these questions, one can discover targets and determine the position and distance of them. The mutual position of various targets can be specified and one can determine the basic properties and motions of radar targets. One can especially determine their size. Within wide limits, one can also determine the direction of the target speed, the roughness of and surface properties of targets, etc. It is possible to detect relative differences in the properties of various targets. This is especially important when observing the Earth's surface using radar. It is quite possible to distinguish water and land or ro[illegible] and buildings from agricultural areas. One can distinguish fields and forests or one can even distinguish various fields with different growth. One other important property for both military and civilian applications is the discovery and identification of point targets, aircraft, land vehicles and ships in their natural surroundings.

The quality of the responses to the questions mentioned above and the remote sensing results to be achieved with radar depends essentially on the range, the resolution and the measurement accuracy of the radar unit. These parameters determine the possibilities and limitations of radar systems.

One important factor for the range of a radar is its transmitted power. The range of radar is proportional to the fourth root of the transmitted power. This means that if one wishes to double the range of a unit at the expense of the transmitted power, the transmitted power has to be increased by a factor of 16. The range of a radar on the other hand is also given by the ratio of signal to noise power (S/N), which can be detected by the radar receiver and can be displayed. This S/N and, therefore, the range can be optimized with optimum signal design in the transmitter and by optimum signal processing in the receiver. In this

Figure 3. Radar image of a river terrain in Holland

way, the quality of radar units can be substantially increased in terms of range, measurement accuracy and resolution. Modern data processing units and electronics make substantial contributions to the possibilities of remote sensing using radar.

Radar units at the Institute for High Frequency Technology

Table 1 shows the data of radar units, which the Institute for High Frequency Technology has available for reconnaissance purposes.

The "E-SLAR" is a simple side viewing radar for use in small aircraft and is used for radar cartography. From an aircraft, it is possible to record a 3 km wide strip of the overflown region to the side from the aircraft. The device for a flight altitude of 1000 m has a resolution cell of about 25 m x 25 m on the surface. Figure 3 shows the results of such a measurement with a river landscape in Holland. One can easily see the river with several ships, different fields of various design as well as paths and roads.

The two frequency scatterometer is used to observe water surfaces. One can determine the state of the ocean in terms of wavelengths, wave height and size and direction of ocean flows. Figure 4 is a representative measurement result which was taken from a platform in the North Sea. Figure A shows the flow speed of the water surface as a function of the test operation using the

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scatterometer during a test duration of 12 hours. This is compared with the water speed at a depth of 9 meters and 23 meters using conventional flow meters. The periodic fluctuation can be found when the tide changes. B is the difference between the water speed at the surface and at a depth of 9 meters. D is the instantaneous wind direction and E is the instantaneous wind speed. The device will soon be operated from an aircraft.

The results of the work with these two radar systems was the basis for the development of the microwave remote sensing experiments (MRSE), which will fly on the spacelab. The construction of this device is under the direction of the main contractor, Dornier. The DFVLR is responsible for the design, operation, data processing and evaluation for users. This MRSE has three operating roads in the X band, at a frequency of 9.6 GHz. It contains a microwave radiometer for calibration and a two-frequency scatterometer for atmospheric observations, to observe the ocean surface and a high resolution radar, a so-called synthetic aperture radar (SAR) for Earth observations. Table 1 shows the radar data of the MRSE. Table 2 contains the data for the MRSE radiometer.

High resolution radar units

In the following we will briefly describe the way in which an SAR operates. The resolution capacity of radar units is determined by the radar antenna size. Modern data technology (German line missing) the capacity for interference with coherence and the currents of frequency displacement when motion takes place, the so-called Doppler effect, however, allow the development of artificial apertures which are much greater than those of the antennas used. A radar is installed in an aircraft so that the antenna looks to the side (perpendicular to the aircraft axis) and therefore, radiates towards the Earth's surface according to its main lobe. The signals reflected from the Earth whose frequencies are changed because of the Doppler effect due to the motion of the aircraft with respect to the radar targets, are therefore, coded. This is recorded in the receiver, stored and later on it is recomposed with the correct phase and process using special methods (very complex). In this way, one can achieve the same effect as with a (line missing) in this direction. For example, for flight altitudes of 10 km, one can achieve path resolutions of 1.5 m. This is also true from the four operations from orbiting satellites. Figure 5 gives such a radar image taken by the satellite Seasat. At a flight altitude of 750 km, one obtains an area resolution of 25 m x 25 m on the Earth's surface so that detailed measurements can be made.

Figure 5 shows the Rhine area from Bonn to Cologne. One can for example see the Cologne-Bonn Airport and the Research Center at Koeln-Porz of the DFVLR on the right half of the photograph. The fine structure is remarkable which still shows the small lakes between Bruehl, Huerth and Kerpen and the fine resolution of the fields (line missing). It then becomes clear what high degree /39
of resolution one can achieve with an SAR. This radar image was created at the DFVLR by the main space flight operations division in Oberpfaffenhofen and even the processing of the radar data for producing such an image is a substantial technical achievement.

Basic remarks about microwave radiometry

The possibilities of a passive position determination of electromagnetic waves (radiometry) depend essentially on the quality of the radiation source. Two types of radiation sources can be distinguished: Natural sources and artificial radiation sources. In the following we will only consider the natural radiation. Any device which detects radiation is a radiometer. A microwave radiometer, therefore, is an extremely sensitive receiver which receives, evaluates and displays microwave radiation which comes from the surroundings of the radiometer. In general, this radiation is incoherent, that is, it has noise. It consists of three parts, the deflected radiation, which comes from space, and which

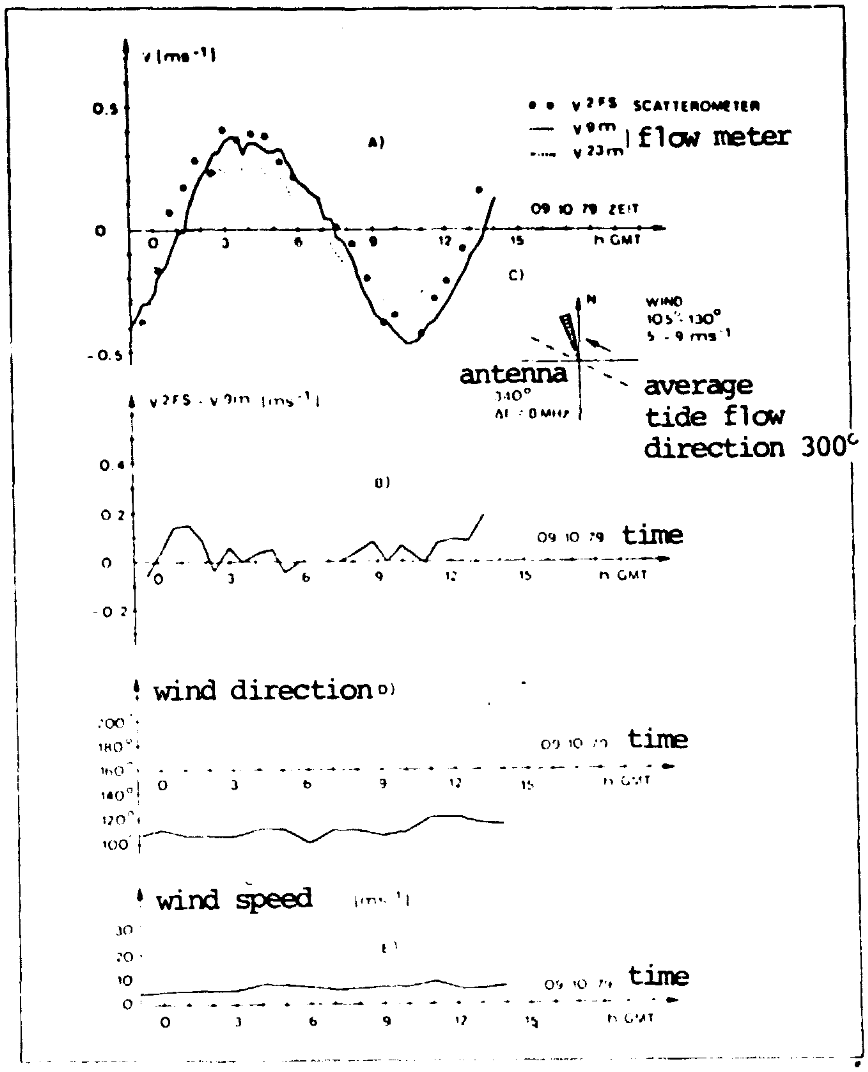

Figure 4. Measurement result of the two-frequency scatterometer.

is reflected at the observed objects, radiation which comes from the objects themselves and a part which is produced behind the objects and penetrates the object. This radiation is equivalent to a temperature according to the Planck law. Therefore, one speaks of thermal radiation or thermal microwave radiation in the microwave range.

In radiometry, therefore, the radiation measurement is

Figure 5. Microwave satellite image of the Rhine country between Cologne and Bonn.

reduced to a temperature determination. Basically, microwave radiometry methods are identical with those of passive infrared measurement methods. The most important difference is in the radiation power levels. For body temperatures around 300 K in the infrared, that is, for a wavelength of about 10μ, the specific radiation power is greater by a factor of 10^4 than for the microwave range. Microwave radiometers, therefore, have to detect power levels on the order of 10^{-12} W. Therefore, much more sensitive sensors and receivers are required for microwave radiometry than for the infrared range.

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Figure 6. Diagram of a radiometer and its operation principle (1 = antenna with directional characteristics, 2 = object (temperature T_o) $\Delta T = T_H - T_o$)

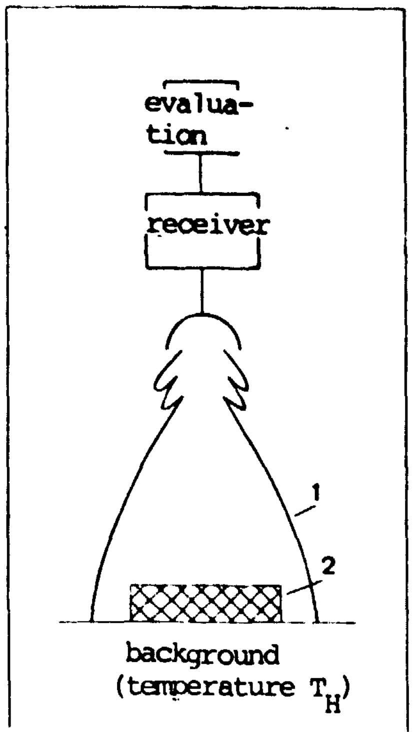

Figure 7. Radiation temperatures of various surfaces at 32 GHz as a function of angle of incidence (polarization--= horizontal, ---= vertical)

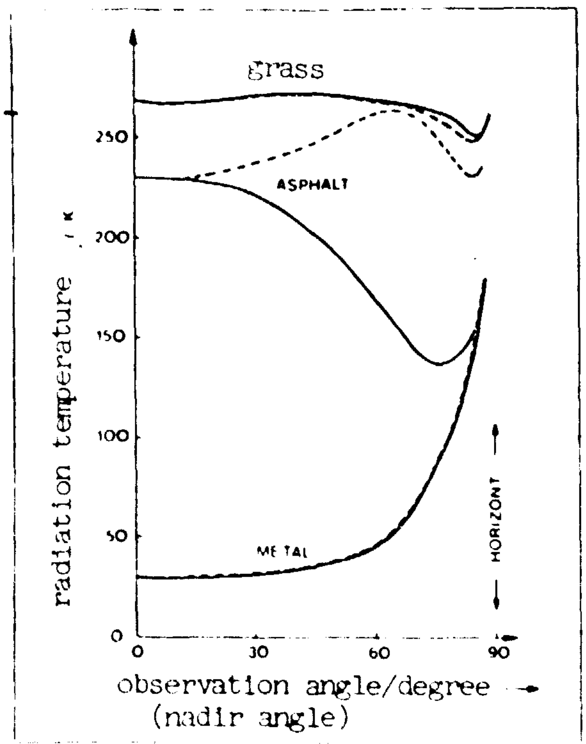

Figure 6 gives the method of operation in the basic design of a radiometer using a block diagram. Basically, a radiometer consists of an antenna with a high focusing, a highly sensitive receiver with the lowest possible eigen noise and a large band width as well as an evaluation circuit. This radiometer establishes the temperature contrast between the measured and desired object and the surroundings of this object. Just like everywhere in radar technology, for radiometry the effectiveness of a system depends on the signal to noise ratio (S/N).

Various objects can then be separated using radiometers and can be recognized as being separate bodies if their apparent temperatures differ. In other words, with radiometers, one attempts to measure temperature contrasts both in the microwave range as well as in the infrared range. If one uses a radio- /40
meter according to Figure 6 to observe an object on the Earth's surface, then in general one also records the apparent temperature of the Earth's surface. The measurable temperature contrasts depend on the nature, shape and size of the objects under consideration, that is, on object parameters. They also depend on the data of the radiometer being used for the measurement, the radiometer parameters. Among the object parameters we have the roughness of the object surface, the material constants, the humidity, etc. The radiometer parameters include antenna data, such as polarization and focusing, band width of the receiver and the integration times. Figure 7 shows the apparent temperatures of various surfaces at a frequency of 32 GHz as a function of the incidence angle. We clearly see that for grass or the Earth's surface with vegetation, the temperature variation up to an incidence angle of 60° is almost constant at 280 K. In this range, the Earth's surface of the shape mentioned is a "black" body to a good degree of approximation. Therefore, there is no dependence on polarization. For a metal plate one finds an apparent temperature variation which increases substantially with increasing incidence angle, but there is no dependence on polarization.

Figure 8. Microwave radiometer photograph from an altitude of 80 meters from a parked aircraft. The color scale extends from white (very cold) to dark red (very warm, here about 300°K)

Frequency	11 GHz	32 GHz	90 GHz uncooled	90 GHz uncooled	9.6 GHz MRSE planned, under construction at Dornier
angle resolution of antenna	2.8°	2.3°	2.3° and 9°	2.3° and 9°	1.1° 2.2°
space resolution	21m x 21m from 460 m altitude	17m x 17m from 460 m altitude	17m x 17m from 460 m altitude	17m x 17m from 460 m altitude	for 45° depression 7.5 km Az x 21 km El from 250 km altitude
temperature resolution	1 K	1 K	2.1 K	1 K	1 K
integration time	10 ms	10 ms	10 ms	1 ms	2 ms
receiver bandwidth	1 GHz	0.6 GHz	2 GHz	1.2 GHz	300 MHz
receiver noise temperature	1150 K	485 K	2500 K	290 K	150 K

TABLE 2. Microwave radiometer of the DFVLR high frequency technology institute.

Figure 9, Microwave radiometer photograph of parking spaces with vehicles (white dots)

In the metal plate, the sky and its unpolarized radiation are mirrored. For an incidence angle of 0°, the metal (missing line) is very cold. This agrees with the fact that a metal plate does not absorb any radiation.

The transparency of the atmosphere has a substantial influence on the radiation temperatures measured by radiometers. This transparency is usually characterized by the attenuation shown in Figure 1. This attenuation depends on frequency, weather conditions in the atmosphere and the atmosphere density, that is the altitude above the ocean surface.

In addition to the antenna and its focusing which determines the angular resolution capacity of the device, the eigen noisiness of the receiver is also important which, should be as low as possible. Also, the band width of the receiver should be as large as possible and the integration time is also an important parameter, that is, the observation duration over which an object is observed. A characteristic parameter which is a measure for the quality of a radiometer is the temperature resolution capacity as a function of these parameters. Essentially, it depends on the square root of the product of band width and integration time. At the present time, in the cm wave range one has a temperature resolution of about 1 K for a few ms of integration time.

Microwave radiometer in the DFVLR

Table 2 shows the data of the microwave radiometers which are presently available and used at the high frequency technology

Institute of the DFVLR.

Figure 8 shows the photograph of an aircraft on the ground using a microwave radiometer. One can clearly see the differences within the concrete parking space of the aircraft as well as the contrast between the concrete and the adjacent grass surface. Figure 9 is a parking area also recorded in the same manner. The white points are the parked vehicles. One can clearly see the access paths and the especially prepared parking areas. The indidivual vehicles in the empty parts of the parking area are also visible on the right side of the image. The images were taken during overflights from an altitude of 80 meters. The reception antenna of the radiometer was looking downward from the aircraft. It was rotated back and forth to the side. The advance was provided by the motion of the aircraft itself. In this way, figures 8 and 9 were produced by a continuous and point-wise scanning of the area, in view of the antenna lobe.

The future

In the future it will be possible to obtain information about the Earth's surface, for example, ground humidity, roughness, urbanization, vegetation and its states independent of the time of day and the weather. Global statements will be made about the state of the ocean, the snow and the ice cover above the ground and the ocean. Microwave sensors will make a substantial contribution to this.