"the temperature measured by this microwave radiometer agrees very well with that of a precision thermometer . . ."

An Improved Microwave Radiometer for Measurements on the Human Body *

by

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Abstract

The construction and performance of a 4 GHz-radiometer for measurements on the human body is presented. The radiometer measures the temperature and emissivity simultaneously and independent of each other. Experimental and theoretical results are given and the resolution of the radiometer is investigated.

Introduction

When determining the temperatures of the human body with microwaves, the use of conventional radiometers may lead to considerable errors. Even if no absolute temperature measurements are necessary, not even temperature differences can be recognized correctly; that is due to the fact that antenna mismatch changes at various parts of the human body. Here especially, such antennas are regarded which are in direct contact with the body, for example dielectrically filled waveguides. The antenna mismatch for a given configuration antenna-body may be described within a certain frequency band by the power reflection coefficient R or by the emissivity E, where

$$E + R = 1 \qquad (1)$$

holds. Consequently, the maximum power available from the object for E = 1, namely

$$P_{obj} = k \cdot \Delta f \cdot T_{obj} \quad , \qquad (2)$$

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with k Boltzmann's constant, Δf the frequency bandwidth and T_{obj} the temperature of the object, is reduced to the radiated power

$$P_{rad} = E \cdot P_{obj} \quad , \qquad (3)$$

which is received by the antenna.

These facts were described in detail in /1/, /2/. To solve the problem and to receive power proportional to T_{obj} and independent of E, it was also proposed not only to receive noise power but also to emit noise power. This is done best if the emitted power from the radiometer P_R equals the available power from the object P_{obj}. So the total power received by the antenna is given by

$$P_A = P_{rad} + R \cdot P_{obj} = P_{obj} \qquad (4)$$

According to this principle, a method was presented in /2/ where the emitted power of a controllable noise source could be varied, however, no details were given on the power variation of the source. Noise power control may be realized by varying the operating point of a semiconductor noise diode. Unfortunately, the emitted power is not directly proportional to the voltage or current of such a noise diode. Therefore, to determine the temperature of a body, the exact characteristic of the noise source must be known.

Furthermore, one runs the risk that variations of the operating point cause a variation of the noise spectrum which may lead to errors.

The Radiometer

The radiometer presented in this paper is a modified balanced Dicke-radiometer with additional components for the radiation of noise power.

To get rid of the nonlinear characteristic of the noise diode with the above mentioned disadvantages, in the procedure described here the operating point of the noise diode is fixed by the voltage U_o in an advantageous range with reference to temperature stability and noise power (Fig. 1). The noise diode is permanently switched on and off with frequency f_3 by an electronic switch. A variation of the average power P_n, or the temperature T_n of the noise diode is achieved by a variation of the pulse duty factor. Whereas the temperature of the object can be determined from this pulse width modulation, the position of the pulses is changed with frequency f_2 about a mean value in order to measure the emissivity of the configuration antenna – human body. With the same frequency the synchronous detector 2 is triggered and so the additional phase modulation is identified. Pulse width and pulse phase modulation are realized by means of an IC, which first generates a strongly linear triangle pulse of frequency f_3, and at the same time and with the same frequency, a square-wave. The modulation of the noise diode is accomplished by the aid of a comparator which compares the triangle signal with a control voltage $U_c = UT_{obj} \pm U_{add}$ (U_{add} additional voltage for phase modulation) and then influences the switch (Fig. 2). Furthermore, the latching circulator as well as the synchronous detector 1 are triggered with the frequency f_1. The control loop is closed by means of an integrator in order to maintain balance between the measuring branch antenna – amplifier and the reference branch noise diode – amplifier.

For a correct investigation of the realized radiometer, imperfections of the utilized components must be taken into account. Then for the temperature of the object follows

$$T_{obj} = \frac{1}{2} a_1 T_n + (1 - \frac{1}{2} a_1) \cdot T_o - \frac{1}{2 E a_3} (a_1 a_3 - a_2)(T_n - T_o) \qquad (5)$$

with

- T_n the time averaged equivalent temperature of the noise diode
- T_o the ambient temperature of all lossy microwave components
- a_1 the linear power attenuation coefficient from the power divider to the antenna
- a_2 the linear power attenuation coefficient from the power divider to the amplifier
- a_3 the linear power attenuation coefficient from the antenna to the amplifier.

The attenuation coefficients also include line losses, adapter losses and transmission losses of both the circulator and the latching circulator. The three terms of this equation may be regarded as a measuring term, an offset term and an error term. Varying the coefficient a_1 with an adjustable attenuator, the last term can be set zero. Then, besides of the offset term, which can be kept constant by controlling the temperature T_o, T_{obj} is proportional to T_n, which itself is proportional to the voltage UT_{obj}.

For the determination of the emissivity E, the following expression can be derived

$$E \sim k \cdot U_E + a_1 a_3 - a_2 \qquad (6)$$

with U_E the output voltage of the synchronous detector 2 and k a constant.

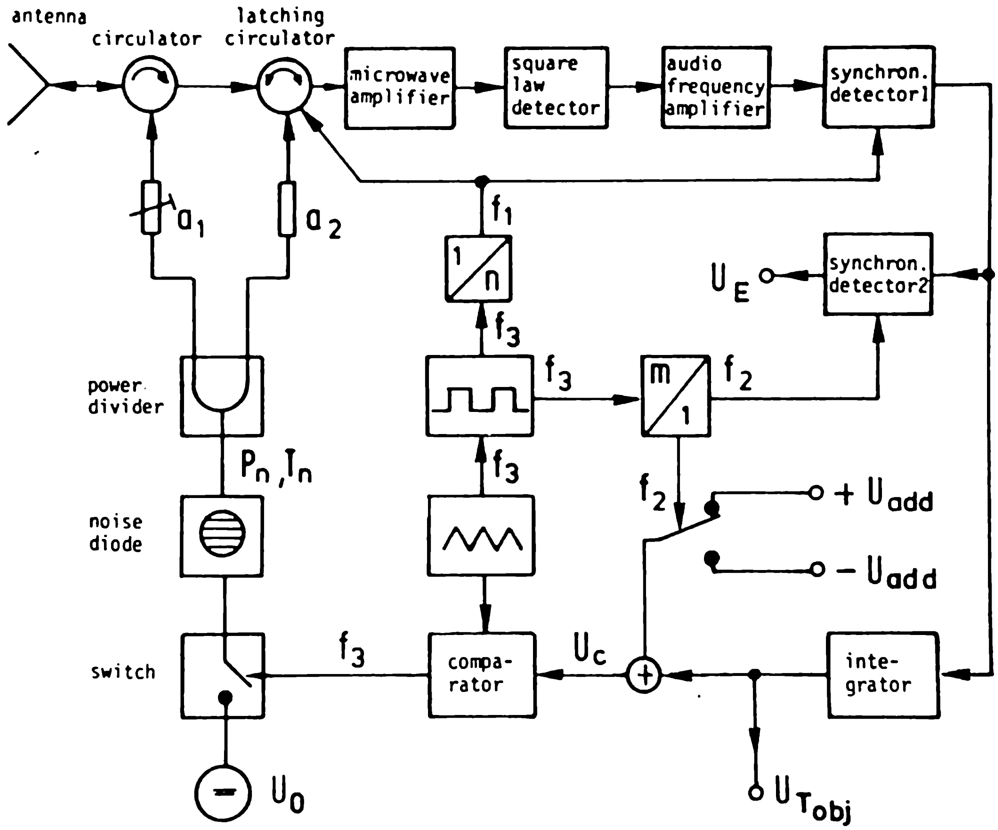

Fig. 1: Block diagram of the microwave radiometer

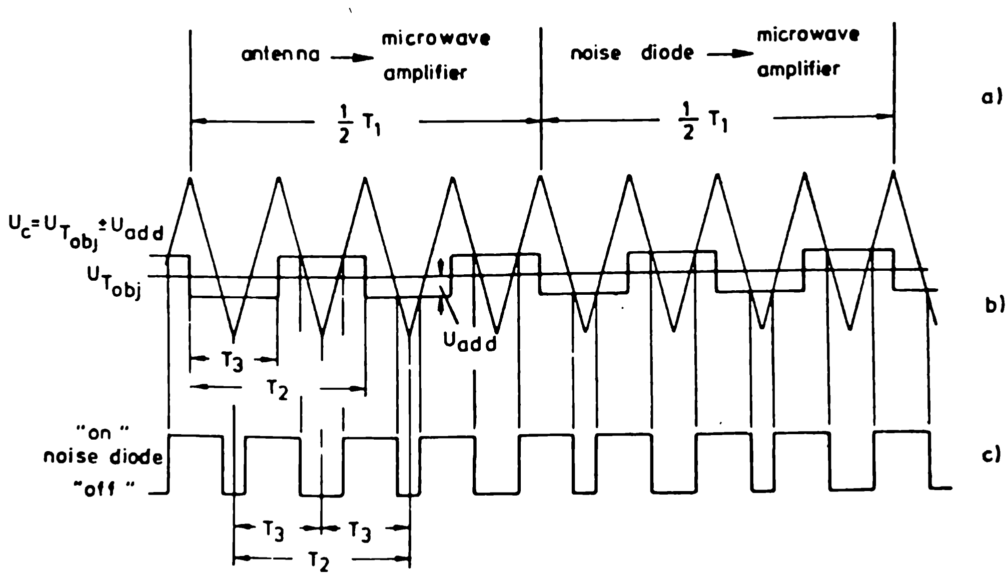

Fig. 2: Modes of operation and signals of the radiometer at the
a) microwave amplifier input c) noise diode
b) comparator

Again, the same calibration procedure as in (5) is sufficient for the last two terms to vanish.

Concerning the resolution of the system, it can be shown, that for the smallest detectable temperature and emissivity differences the relations

$$\Delta T_{obj} > \frac{T_{sys}}{a_3 \cdot E} \sqrt{\frac{2}{\tau_1 \Delta f}} \tag{7}$$

and

$$\Delta E > \frac{T_{sys}}{a_1 a_3 \; T_{add}} \sqrt{\frac{2}{\tau_2 \Delta f}} \tag{8}$$

hold,

where T_{sys} is the overall equivalent noise temperature of the whole device including the noise power received from the object, $\tau_{1,2}$ are the time constants of the system and T_{add} is the additional noise temperature of the noise diode caused by the voltage U_{add}. Though the radiometer cancels variations of the emissivity for temperature measurements, it is obvious, that E should be as large as possible. Furthermore, it is clear, that losses from the antenna to the amplifier should be kept small.

The radiometer consists of two modules, one with the microwave components and, additionally, an audiofrequency preamplifier, and another with the remaining electronic circuitry. A picture of the microwave set-up is shown in Fig. 3.

In order to control the temperature, most microwave components are incorporated in an aluminium block, the temperature of which is kept constant at $T_o = 30^o\ C \pm 0.05^o\ C$.

The logarithmic attenuation from the antenna output to the microwave amplifier input is $a_3' = 0.8$ dB and those from the power divider to the antenna and from the power divider to the microwave amplifier are $a_1' = 45.2$ dB and $a_2' = 46$ dB respectively. The gain of the microwave amplifier is 52 dB and its noise figure is 1.7 dB. Varying the pulse duty factor, the average noise diode temperature can be varied between T_n min $= 110 \cdot 10^3$ K and $T_{n\ max} = 790 \cdot 10^3$ K.

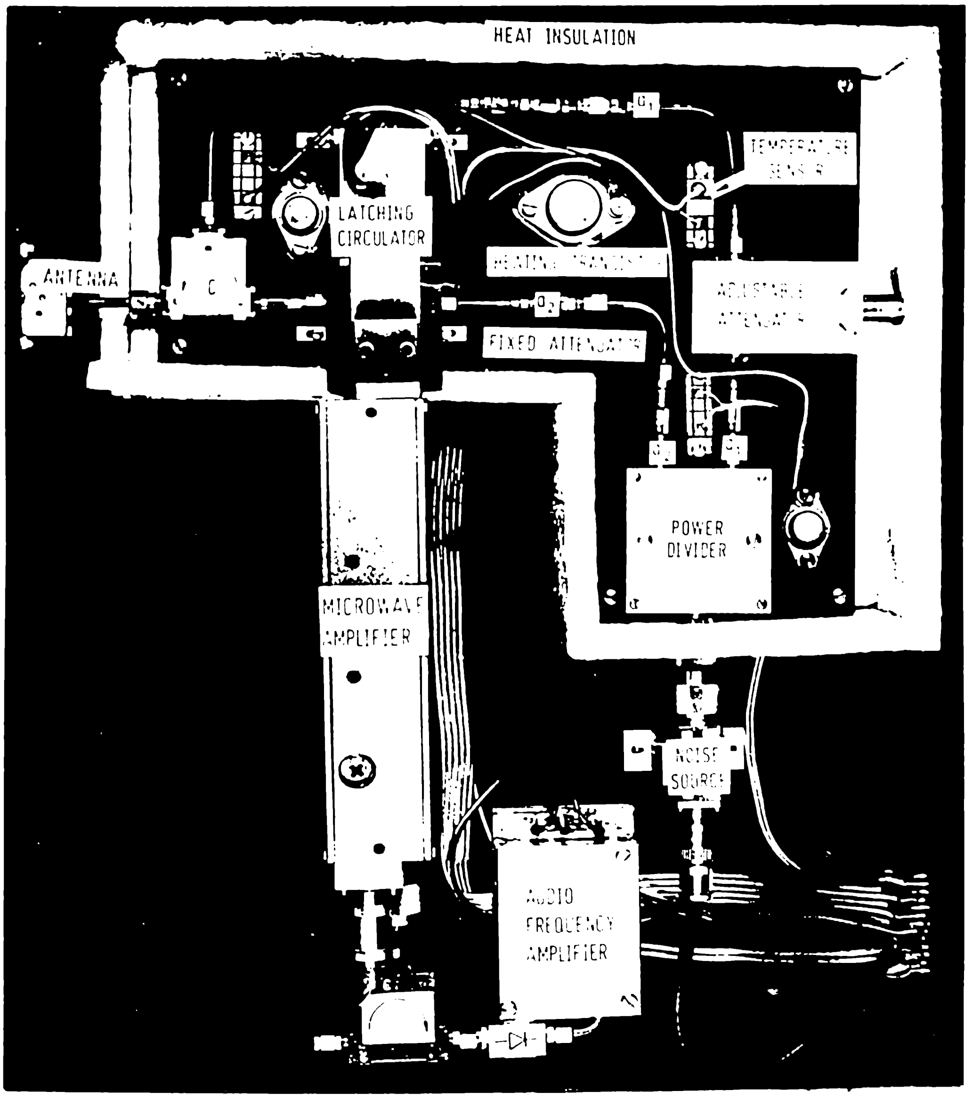

Fig. 3:
Photograph of the microwave components
of the radiometer

Experimental Results

The temperature measured by this microwave radiometer agrees very well with that of a precision thermometer in the whole temperature range for emissivities $E_T > 0.6$ (Fig. 4). Near the limits of the measurement range, due to imperfections of the set-up, slight deviations between the indicated and the true temperature can be recognized for emissivities $E_T < 0.6$. In Fig. 5 it is shown for three temperatures how the emissivity E_R, indicated by the radiometer, depends on the true emissivity E_T.

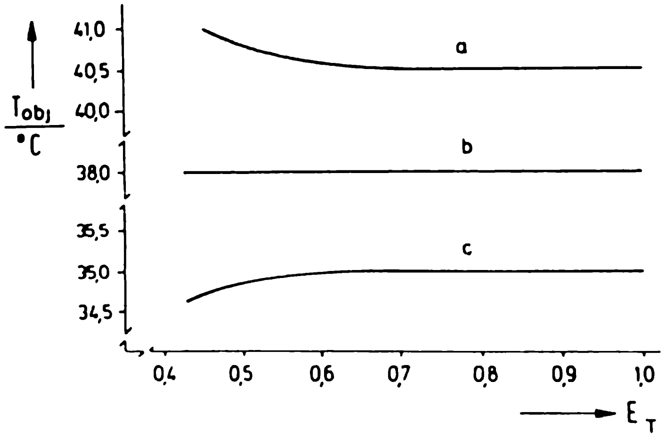

Fig. 4:
T_{obj} as a function of the emissivity E_T for the temperature
a) 40.5° C, b) 38.0° C,
c) 35.0° C

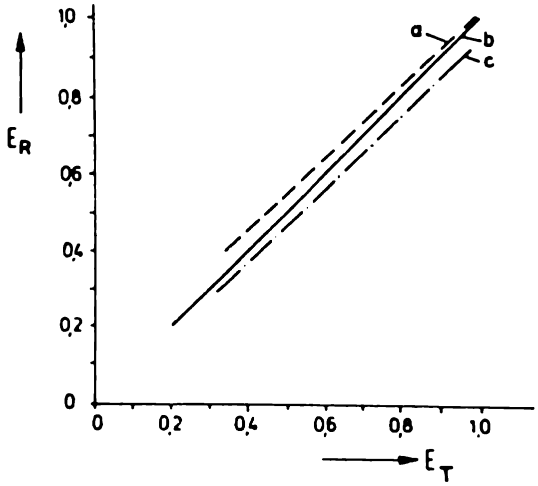

Fig. 5:
The emissivity E_R as a function of the true emissivity E_T for the temperatures
a) 40.5° C, b) 38.0° C,
c) 35.0° C

The experimental results may be summarized in the following specifications:

frequency bandwidth Δf:	3.3 GHz . . . . 4.2 GHz
temperature T_{obj}:	
measurement range	33.5^{o} C . . . . 43.0^{o}C
accuracy	$T_{obj} \pm 0.1^{o}$C
resolution	$\Delta T_{obj} < 0.1^{o}$C
time constant	$\tau \approx 0.2$ s
emissivity E:	
measurement range	0.45 . . . . 1.00
accuracy	E $\pm$ 0.03
resolution	$\Delta E < 0.01$
time constant	$\tau \approx 0.2$ s

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