# SOME THEORY AND PRELIMINARY EXPERIMENTS ON MICROWAVE RADIOMETRY OF BIOLOGICAL SYSTEMS

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Abstract

The theory of microwave radiometry of biological systems is outlined. To check theoretical predictions, an X-band microwave radiometer of the correlation type has been built. More recently, a new series of experiments have been conducted with a self-nulling Dicke radiometer operating at 9.2 GHz. Preliminary experiments performed on humans and some lower animals and plant vegetation show, in principle, the correctness of the theory.

## Introduction and Theory

Radiometry stems from the fact that all bodies of our known physical universe emit electromagnetic radiation according to Planck's law. It can be shown that the power P emitted per unit of area by a body at absolute temperature T°K and per unit of band width (at a centre frequency f) is given by:

$$P(f)=\frac{2\pi hf^3}{c^2}e[\exp(hf/kT)-1]^{-1}\frac{\text{watt.sec}}{\text{cm}^2}$$

where e is the emissivity of the body (generally a function of frequency, temperature and direction; for a perfect black body $e_B=1$, but for a grey body $e_G<1$),

and where h is Planck's constant (Joule sec)
k is Boltzmann's constant (Joule $°K^{-1}$)
and c is the velocity of EM waves in free-space (cm $sec^{-1}$)

However, for moderate temperatures in the frequency region for which f<<kT/h = 20.8 T GHz (MW region), Planck's distribution formula reduces to the Rayleigh-Jeans expression,

$$P(\Delta f)=\frac{2\pi kT}{c^2}ef^2\Delta f$$

Sophisticated radiometric techniques have made possible the measurement of minute amounts of energy in the microwave region of the electromagnetic spectrum.

It can be shown that the minimum power P that a radiometer of bandwidth Δf can detect from an emitting region at absolute temperature T and with emissive properties e is given by:

$$P = e\ k\ T\ \Delta f \quad \text{watts}$$

For a region with e ≃ 1 at T ≃ 300°K, the minimum power, assuming Δf = 1 MHz, is ~$4.0 \times 10^{-15}$ watt.

On the other hand, the minimum detectable temperature ΔT (min), or sensitivity, of a radiometer is equal to the RMS noise temperature of the system as given by:

$$\Delta T_{min} = \frac{K_e T_{sys}}{(\sigma n\ \Delta f)^{\frac{1}{2}}} = \Delta T_{RMS}$$

where $T_{sys}$ is the system noise temperature (°K),

$K_e$ is a sensitivity constant that depends on the type of receiver and its mode of operation,

σ is the postdetection integration time (sec.), and

n is the number of records

From the above expression it is not difficult to show that for a conventional radiometer with σ = 10 sec., $T_{sys}$ = 200°K, Δf = 1 MHz, n=1 and $K_e$ = 1.41 (correlation radiometer), minimum apparent temperature (Ta = eT) variations of 0.1°K and less are easily obtained.

Microwave radiometry has proved to be an exceptionally valuable technique in radioastronomy, and its uses have been extended considerably, mainly associated with remote sensing devices in a variety of applications. However, the use of microwave radiometry to study biological systems has not as yet been explored. The authors' calculations show that this technique may prove a powerful tool in the fields of biology and medicine, and may facilitate studies on the problem of biocommunication.

Experimental data indicates that the dielectric properties of different tissues or components of human and other animal bodies (and presumably of plant vegetation) vary substantially. The dielectric properties of tissues are dependent on the frequency of the radiation. From the real (ε') and imaginary (ε") parts of the complex dielectric constant, $\varepsilon^* = \varepsilon' - j\varepsilon''$ (both obtained from literature), the authors have calculated the emissivities of several tissues at different frequencies with the aid of Fresnel's equations. For the case of vertical viewing, these equations reduce to the simplified expression:

$$e=1-\left|\frac{1-\sqrt{\varepsilon^*}}{1+\sqrt{\varepsilon^*}}\right|^2$$

Calculations show that the emissivities obtained for the several tissues at a given frequency differ from each other sufficiently to allow for the detection (by means of conventional MW radiometric techniques) of their different apparent (brightness) temperature $T_a$. The parameters ε', ε" and e for several tissues at four different MW frequencies are shown in Table 1. All animal tissue data given in Table 1 (except for bone) refers to a thermometric temperature of 37°C and to normal (healthy) tissues. The plant tissue data, also given in Table 1, refers to a thermometric temperature of 24°C. Calculations have been extended to abnormal tissues as well, to show that because of their different dielectric properties, differences between normal and abnormal tissues (of the same type) can also be determined by MW radiometric techniques. These facts indicate that this could be a highly functional technique in medicine and biology.

On speculative grounds, MW radiometric techniques could be also extended to detect changes of state (physiological, emotional, etc.) in living systems. Biological systems (including man) can voluntarily, or as a reflex action, alter their states to accomplish certain specific functions. Changes in a given state are usually accompanied by changes in: i) the local or total thermometric temperature, ii) metabolic rate, iii) gas and liquid exchange rate (i.e. transpiration, etc.), iv) nervous and muscular activity, v) electric conductivity and biopotential of tissues, and many other changes. All these adjustments are interdependent to some extent. From scattered experimental data (relative to electrical and thermal conductivities and temperature changes observed in biological systems undergoing specific state changes of different nature) one can calculate that it is possible in principle to detect some of these changes (some experimental evidence is given later).

Based on the results of preliminary calculations, an X-band microwave radiometer of the correlation type with a sensitivity of a fraction of one degree Kelvin has been built and operated. A block diagram of this radiometer is shown in Figure 1. More recently, a refined version of a Dicke radiometer operating on the self-nulling principle with a centre frequency of 9.2 GHz and a bandwidth of 100 MHz has been used in the experiments.

## Experimental Technique

In order to check the validity of the theory presented here, experiments were performed with human subjects, rabbits, cats, mice, rats, guinea pigs and plant tissues. Experiments were conducted in a large MW anechoid chamber. The experimental apparatus used is shown in Fig. 2.

Figure 2 also shows an antenna protruding from the ceiling. This antenna forms part of the equipment normally used to conduct MW irradiation experiments on biological systems and should be ignored here. The front end of the radiometer (antenna and MW circuitry) was installed in the chamber which was kept under close environmental control. The axis of the radiometer's antenna subtended an angle of 45° (approximately) with respect to the floor. To minimize disturbance of the natural MW emission from the system (due to nearby structural materials), the specimens under investigation (except for human subjects) were positioned on a thin polyethylene sheet mounted on a plexiglas frame, suspended from the ceiling of the chamber by pulleys as shown in Fig. 2. Both polyethylene and plexiglas are fairly transparent materials to X-band MW frequencies. In order to enhance the brightness temperatures (directly related to the natural MW emission), the subjects under study were viewed, by the 7° beamwidth radiometer's antenna, against a cold background. This background consisted of the "loaded" side of an eccosorb (FR340) block (53 X 36 cm) immersed in a styrofoam container partially filled with liquid nitrogen. The eccosorb block (slightly smaller than the container) floated on the liquid nitrogen which was kept at a constant level. To minimize heat radiation from the container, its top was covered by a thin polyethylene sheet. This simple arrangement provided a fairly constant background corresponding to a brightness temperature of about 268°K.

## Experimental Results

Experiments involved determining the brightness temperature of several biological systems in:
(i) their normal state and (ii) under the influence of drugs introducing some specific change in their natural state. Depending upon the nature of the experiment the specimens (except for human subjects) were placed either in thin teflon or plexiglas containers (the top side facing the antenna either being kept open or covered by a thin polyethylene sheet) or directly on the platform described above.

Figure 3 shows the radiometer's signatures from a human subject corresponding to his head, hand and back respectively. These recordings are not directly comparable due to the different beamwidth areas of the antenna covered by the three different portions of the body.

Figure 4 shows the signatures corresponding to six rats (arranged in a symmetric geometrical pattern covering a large portion of the antenna beamwidth) to which the drug AIA (allyl-isopropyl-acetamide) was administered. The first recording (A) was taken shortly after injection, while recordings B and C were obtained one hour and two hours respectively after administering the drug. Experiments using Pentobarbital on rats, cats, rabbits and guinea pigs showed a similar pattern. However, differences were observed according to the kind of animal, drug concentration and type of drug used. Experiments (not reported here) with Atropine and other drugs have also been conducted.

## Discussion

Not only is the measurement of natural MW emission from biological systems possible, but the detection of changes in their state (physiological, emotional, etc.) is also feasible, as has been shown indirectly above. The changes detected in the brightness temperature can be due to variations in the: dielectric properties of the tissues, to thermometric temperature changes, or a combination of both. Both are induced by upsetting the complex biochemical balance of the system in a given state. In the cases presented here (i.e. treatment with Pentobarbital and with AIA) the effect is a decrease in the brightness temperature of the specimens, which is to be expected (apart from more subtle mechanisms) due to the state of deep hypothermia which they produce.

Since administration of certain drugs can induce specific effects which characterize some of the different normal states (i.e. due to natural causes) experienced by the biosystem, chemicals provide us with a simple means of investigating the effect of such states on natural emission in the MW region. In addition, from data pertaining to the depth of penetration and the absorption and reflection coefficients of the tissues involved (at the operating frequency), the different contributions due to air-skin-fat- muscle-bone systems may be inferred. This analysis can provide a wealth of information. However, the analysis is not straightforward.

In summary, preliminary experiments indicate the correctness of the theory outlined above. They also show that MW radiometry may provide information not readily available from more conventional techniques.

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Table 1 Dielectric and Emissivity Data*

| ε' | ε" | e | f | Tissue |
|---|---|---|---|---|
| 43.00 | 10.00 | 0.452 | | Bamboo, leaf, young |
| 41.00 | 20.00 | 0.440 | | Dandelion, leaf, old |
| 39.00 | 7.80 | 0.471 | | Sugar maple, leaf, young |
| 40.00 | 8.00 | 0.466 | 1.00 GHz | Tuliptree, leaf, young |
| 50.00 | 6.20 | 0.432 | | Tuliptree, branch, outer layer |
| 33.00 | 2.40 | 0.504 | | Branch, wood material |
| 53.00 | 15.00 | 0.415 | | Whole blood |
| 70.00 | 22.50 | 0.370 | | Blood serum |
| 43.50 | 16.50 | 0.440 | 3.00 GHz | Skin |
| 6.90 | 1.60 | 0.791 | | Fat |
| 45.00 | 23.00 | 0.423 | | Whole blood |
| 57.50 | 24.00 | 0.393 | | Blood serum |
| 35.50 | 16.00 | 0.468 | 9.43 GHz | Skin |
| 4.50 | 0.95 | 0.865 | | Fat |
| 7.60 | 1.45 | 0.776 | | Bone |
| 32.00 | 20.00 | 0.467 | | Whole blood |
| 45.50 | 29.00 | 0.408 | | Blood serum |
| 23.00 | 13.00 | 0.532 | 23.62 GHz | Skin |
| 3.40 | 1.10 | 0.899 | | Fat |
| 6.30 | 1.10 | 0.810 | | Bone |

* The values for ε' and ε" for animal tissue have been taken from T.S. England, Nature, 166, p. 480 (1950), while their values for plant tissue have been taken from W.R. Tinga and S.O. Nelson, the J. of Microwave Power, V. 8, No. 1, 1973.

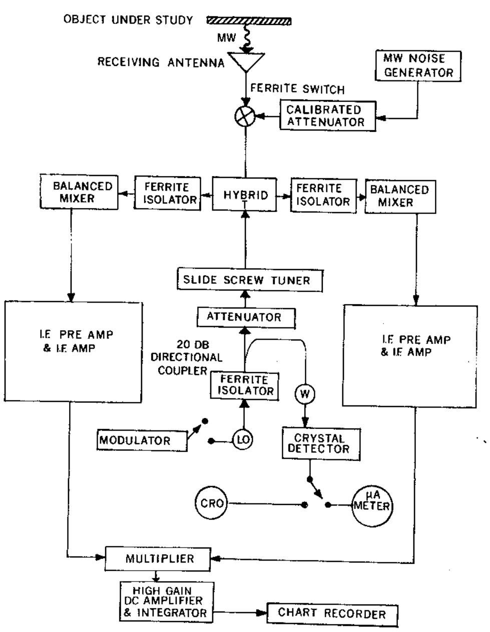


Fig. 1 CORRELATION RADIOMETER

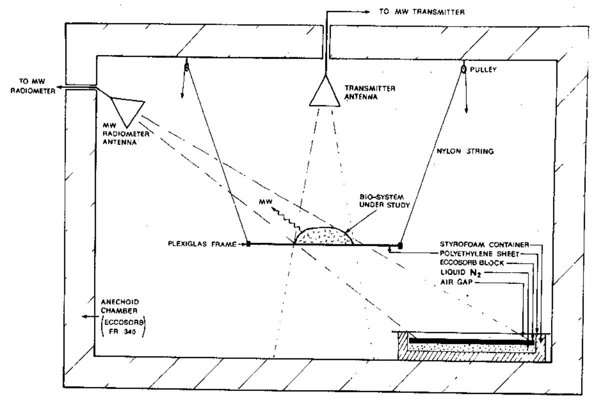


FIG. 2 EXPERIMENTAL FACILITY USED TO MEASURE THE NATURAL MICROWAVE EMISSION FROM BIOLOGICAL SYSTEMS

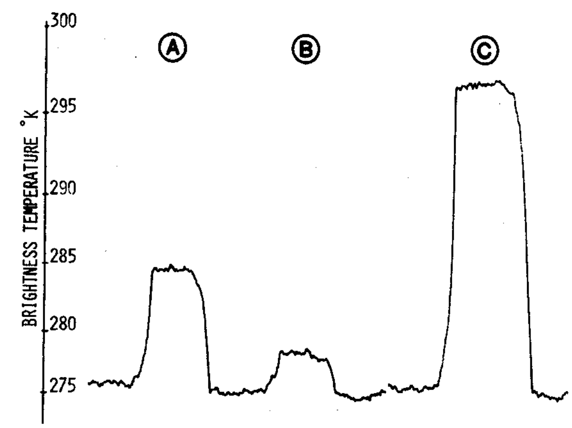


FIG. 3 X-BAND (9.2 GHz) RADIOMETRIC RECORDINGS FROM DIFFERENT PARTS OF A HUMAN SUBJECT: (A) HEAD, (B) HAND AND (C) BACK

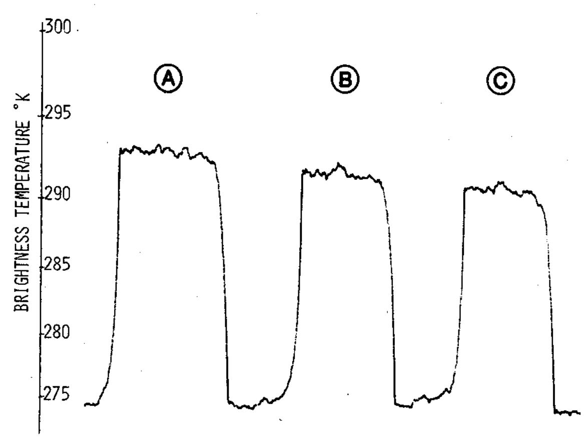


FIG. 4 X-BAND (9.2 GHz) RADIOMETRIC RECORDINGS FROM MICE INJECTED WITH AIA. THE ABOVE SIGNATURES WERE TAKEN AT DIFFERENT TIMES AFTER ADMINISTERING THE DRUG: (A) 0 H., (B) 1 H. AND (C) 2 H.

NOTES