PASSIVE FOUR-FREQUENCY MICROWAVE TOMOGRAPHY: AN EXPERIMENTAL FEASIBILITY STUDY

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Abstract: A newly developed multi-frequency radiometric system is being used in conjunction with a prototype Microwave Radiometry Imaging System (MiRaIS) that has been developed and used during the past few years for feasible brain intracranial applications. The operation principle of the system is the detection of the chaotic radiation emitted by any material object being at a temperature above the absolute zero. Experiments have already been conducted using single frequency radiometric receivers exhibiting the system's ability of measuring temperature and conductivity variations in phantoms and biological tissues. In the present paper temperature and spatial resolution phantom experiments using the proposed multi-frequency system are reported and discussed taking into account previous theoretical considerations. The multiband radiometric measurements lead to 3D tomography images, since detection depth and focusing region in the medium under measurement are frequency dependent. Further research is required in order to assess the possibility of MiRaIS becoming in the future a useful clinical complement to conventional brain imaging techniques.

Introduction

The present paper discusses the potential value of a prototype passive four - frequency microwave tomography system that has been designed and developed for feasible intracranial applications by utilizing the well-known focused microwave radiometry technique. The latter constitutes the science that comprises the measurement of the chaotic thermal electromagnetic radiation emitted by any lossy media, in any form gas, solid, liquid and plasma being at a temperature above the absolute zero.

Due to the centimetric wavelength dimensions of radiation at low microwave frequencies (1-5GHz), the radiation emitted by tissues up to several centimetres of depth from the body surface can be detected. Since its inception in the early 70's microwave radiometry has been implemented in many specialties of medicine e.g. Neurology, Gynecology, Urology, Pathology [1]-[7] as a clinical diagnostic method as well as in parallel with Hyperthermia, for temperature distribution imaging of biological tissues. Nevertheless, the intracranial applications [1] of the method focused on measuring cerebral temperatures are limited because of the high structural, functional and electrical inhomogeneousness and complexity of the human brain.

The scope of the present research is the development and feasibility study of a prototype multiband microwave imaging system operating in the range 1.0-3.1GHz using Focused Microwave Radiometry for brain imaging**.** The measurements are realized in a non-invasive, totally passive contactless manner fact that constitutes one of the most important advantages of the methodology in question: its totally passive, harmless and painless character.

Figure1. The Microwave Radiometry Imaging System

The basic fundamentals of the proposed methodology are mainly two: On one hand the *Quantum Theory* with the black body radiation and on the other, a *Geometrical Optics* approach with the use of an ellipsoidal conductive wall cavity that is being used to achieve beamforming and focusing. The novelty of this imaging methodology lays exactly in the use of the ellipsoidal cavity-reflector to achieve maximum peak of radiation pattern in order to measure the intensity of the microwave energy, radiated by the medium of interest.

The above mentioned ellipsoidal cavity configuration for focused remote sensing is combined with a radiometric receiving system. The basic parts of a radiometric receiver are a sensitive broadband receiver and the relevant receiving antenna while two types of radiometers are mainly designed and constructed: total power and correlation radiometers. The radiometric receiving system used in the present study is a microwave total power radiometer and relevant non-contacting antenna operating in the range 1.0-3.1GHz.

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An actual photo of the **Mi**crowave **Ra**diometry **I**maging **S**ystem (MiRaIS), as it is in its present state is depicted on Figure 1.

Research regarding the design, construction, experimental testing and refinement of the MiRaIS has been ongoing the past few years in the Microwave and Fibre Optics Lab (MFOL) of the National Technical University of Athens (NTUA). During this period extensive experiments have been performed using two single frequency total power radiometric receivers operating at 1.5GHz and 3.5GHz while thorough electromagnetic analysis in respect of the system's focusing properties inside human head models has also been realized [8]-[13].

According to previous experimental results the system shows the ability of measuring temperature and conductivity variations in phantoms and biological tissues [8]-[13]. Water phantom and animal experiments demonstrate that the voltage output from the system is linearly correlated with the actual temperature of the subjects of interest, fact that is expected when the conductivity of the media under measurement remains unchanged [8]-[11]. Experimental data from cylindrical shaped saline or de-ionized water filled tank phantoms in which saline solutions of different concentrations were infused, provide promising results concerning the system's capability of detecting conductivity variations in phantoms at 3.5GHz [12].

It is worth noticing at this point that the system has been also used on healthy human volunteers that participated in two well standardized psychophysiological tests: the CPT (Cold Pressor Test), which is a standard experimental condition inducing pain and an adaptation of the Hayling test, which is a verbal inhibition and initiation test [9], [13]. Analysis of the measured data indicates the potential value of using focused microwave radiometry to identify brain activation mechanisms potentially attributed to brain tissue conductivity changes. These variations could be possibly involved or affected in operations generated under specific psychophysiological tasks such as the above mentioned tests. These observations could reveal unexplored aspects of microwave radiometry beside the classic clinical applications, such as to realize, non-invasively, feasible imaging of brain activation possibly attributed to tissue conductivity changes [9], [13].

Following this research, a new multiband receiver has been designed and constructed in our laboratory and has been used in conjunction with the existing experimental setup for temperature and conductivity phantom experiments. One of our group's research scopes is to use the enhanced system in phantom and human experiments in order to measure sequentially or in parallel the region of interest in more than one microwave frequency bands. This way, the reconstructed images through the inverse problem solution obtained from the multiband radiometric measurements will provide 3D tomography images, since detection depth and focusing region vary with frequency [14], [15].

In this paper a small overview of the various system modules as well as the theoretical background of the proposed imaging system are presented. The conducted phantom experiments are in detail described and the results are discussed. Finally, the outcome of the present research is summarized in the conclusions section.

Materials and Methods

The innovative MiRaIS, as it has been previously mentioned, consists of a conductive wall ellipsoidal reflector for focusing, a radiometric receiver and a data acquisition and processing system (Figure 1). The conductive ellipsoidal reflector ensures the system's ability of focusing and remote sensing. A four-frequency-band radiometer with a broadband discone antenna operating within the range 1.0–3.1 GHz have been recently developed to obtain measurements of the product of temperature and conductivity of cortical areas in a completely non-invasive manner, corresponding to the detection depth and spatial resolution predicted by the theoretical analysis [14].

More specifically, the MiRaIS consists mainly of two parts: the *analogue module*- i.e. the ellipsoidal conductive wall reflector, a non-conductive wooden supporting construction, the sensitive multifrequency microwave receiver with a relevant broadband antenna and a laser system for positioning; the *digital module*, consists of a motor controller for three dimensional raster scanning movement and a PC for data acquisition and process [8]-[16].

The concept of using an ellipsoidal reflector exploits the geometric property introduced by Appolonius of Perga (2nd Century B.C.) that every ray originating from one focus will merge on the other focus with the same path length following the relevant ray-tracing model. For this reason, the system has been constructed in such a way that the human head is placed at one focal point of the ellipsoidal cavity, while at the other focal point, the convergence of the thermal/chaotic energy radiated in the microwave frequency range from the human brain is sensed by the receiving antenna [8]-[16].

Each measurement with the MiRaIS is performed after the correct and accurate positioning of the area under measurement inside the cavity. The person or phantom is inserted inside the ellipsoidal through an opening and the region under measurement is placed on the focal point. The emitted energy is detected by the antenna placed on the other focus through reflection on the ellipsoidal conductive walls. The signal is then fed to the receiver followed by the pc for the data process. The ellipsoidal cavity that has been constructed is made of fibreglass and has an inner highly conductive nickel coating [8]-[16].

The newly developed four-band radiometric receiver has been entirely designed and constructed in our laboratory [14]. At the front-end of the receiver a low noise amplifier is placed. In order to minimize the noise figure, the LNA is separately housed and connected directly to the antenna port, while the rest of the radiometric system which is the filter bank and the logarithmic detectors with the baseband low noise amplifiers, are housed in a different box and are connected together by a coaxial cable. Two are the main key points of this radiometer: the low noise figure of the amplifier at the front-end and the high dynamic range of the logarithmic detectors (60dB linear) after the filter bank [14]. Additionally, cooling of the LNA is used to achieve gain compensation and metal inserts are placed inside the metallic box where the filter bank is housed to ensure the maximum possible isolation of each channel. Graphs of the frequency response of the filter bank show that due to the filter high class very good rejection is obtained to the neighbouring centre frequencies [14]. An actual picture of the radiometric receiver is depicted on Figure 2.

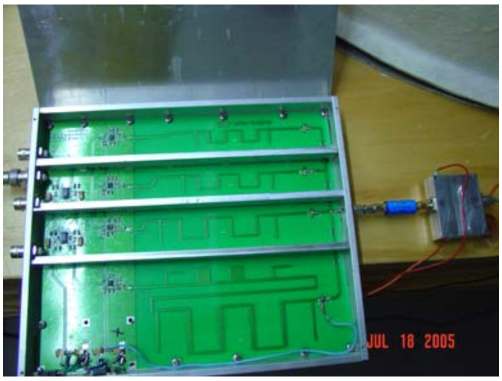

Figure 2. Multi-frequency radiometer operating in the range 1.0-3.1GHz

The antenna that was designed and constructed is a wide band discone antenna with a low cutoff frequency 1.0GHz (Figure 3).

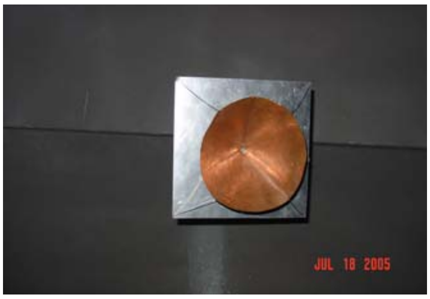

Figure 3. Actual photo of broadband discone antenna

The theoretical issues that have to be examined in the framework of the present research are mainly two: the system focusing properties, which have already been in detail studied [8], [9] and the relation between the radiometric output voltage and the properties of the media under measurement [10]. Regarding the latter as it has been theoretically shown in the past [9], [17] the measured receiving power quantity by a radiometer is proportional to the receiver bandwidth, to the product of temperature and conductivity of the measured media and to a field factor which is a strong function of spatial coordinates, which is defined by the system's focusing properties that are ensured by the use of the ellipsoidal conductive wall reflector.

In order to examine and estimate the system's focusing properties electromagnetic analysis has been performed using two different techniques: a semi-analytical analysis based on Green's function theory and a commercial FEM simulation tool [8], [9]. By observation of the simulation and numerical results it is concluded that in the range 1.3-3.1GHz imaging of the head model areas placed at the ellipsoid's focus is feasible with a variety of detection depths and change of the spatial resolution, depending on the frequency used. According to the numerical results the detection depth varies from 1.8cm to 5cm while the spatial resolution (3dB focusing region) from 1cm to over 3cm, for the higher and lower operation frequency respectively [8]-[15].

Taking all of the above into account, conductivity measurement by microwave radiometry theoretically constitutes a possibility, offering a valuable alternative for passive conductivity measurements of biological tissues, in a non-invasive, completely passive way, besides the in-depth temperature measurement of biological tissue, which is the "classic" clinical application of the methodology. So, in order to investigate the system's potentials and to explore the possible clinical of such a diagnostic tool two types of experiments should be performed: temperature imaging and conductivity variation imaging.

In the framework of the present research water phantom validation experiments were realized. A small container filled with warm de-ionized water is placed at one of the ellipsoid's focal point while the emitted energy is sensed by the receiving antenna placed at the other focus. Both temperature and spatial resolution experiments were conducted and are reported in the following section. Concerning the conductivity variation imaging, recent measurements performed using the enhanced multiband MiRaIS show that the system is able of detecting conductivity variations in saline solutions by observation of the changes of the measured output voltage during the relevant time periods when local saline solution concentration variations occur [16].

Results

Two types of experiments were realized using de-ionized water phantoms with constant conductivity: temperature resolution and spatial resolution. For both tests a small (2cmx2cmx2cm) water container was used.

Initially, the water phantom was filled with water at 45^oC and was placed at the ellipsoid's focal point and was left there to cool until it reached 39^oC. The results are depicted on Figures 4 and 5. The output radiometric voltage is linearly correlated with the water temperature, fact that is expected in the case where the conductivity of the media under measurement remains unchanged. As it is concluded by the experimental results the system temperature resolution is 4mV/1°C at all four radiometric frequencies.

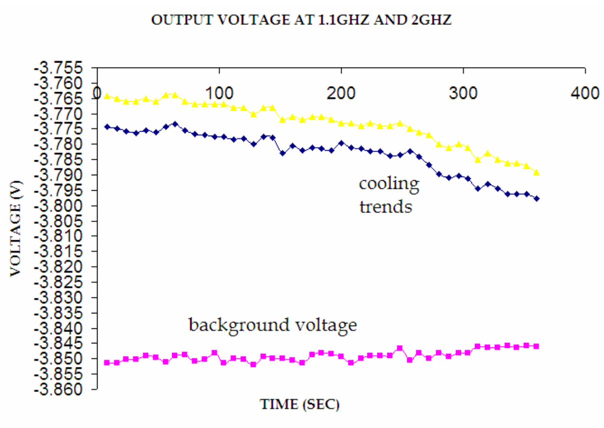

Figure 4. Output radiometric voltage at operating frequencies 1.1GHz and 2GHz

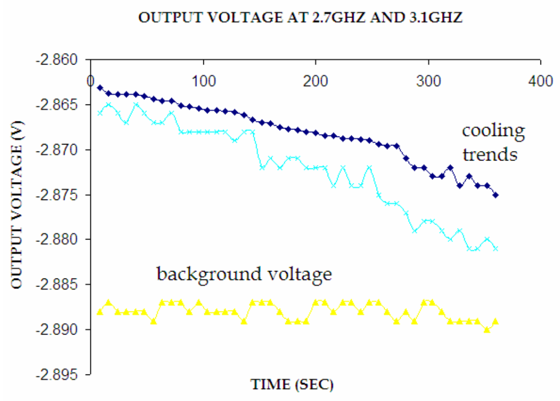

Figure 5. Output radiometric voltage at operating frequencies 2.7GHz and 3.1GHz

Following, two types of experiments aiming at estimating the system's spatial resolution were conducted: linear and 2D (surface) raster scans of the small water phantom at all four operating frequencies of the radiometer.

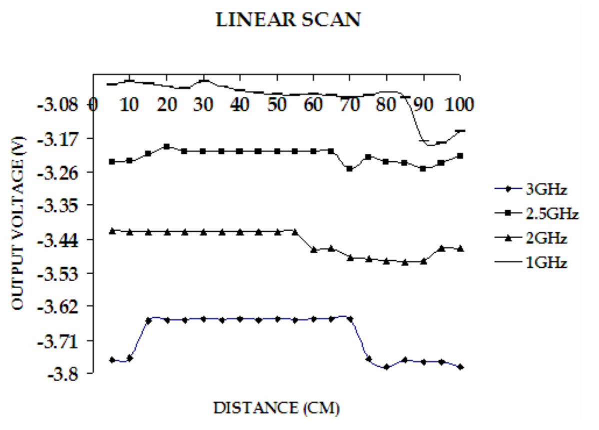

Figure 6. Radiometric voltage measurements of water phantom linear raster scan

The results are depicted on Figure 6. It is observed that at 3GHz and 2.5GHz the physical dimensions of the phantom adequately coincide with the ones that are "radiometrically" detected while a larger focusing area is observed at the other two frequencies**.**

Towards the effort of refining and verifying the linear scan measurements, 2D surface scans of the same phantom were performed using the lower and higher radiometric operating frequencies. Once again a large focusing area is detected at 1GHz while adequate spatial resolution is achieved at 3GHz.

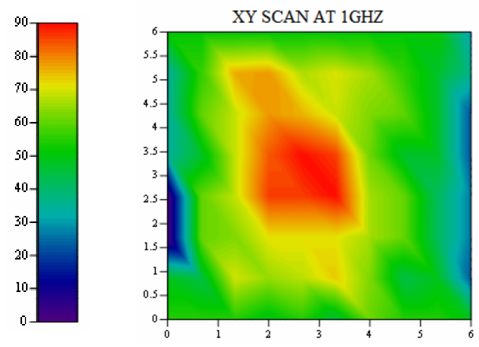

Figure 7. Surface (2D) scan of water phantom at 1GHz

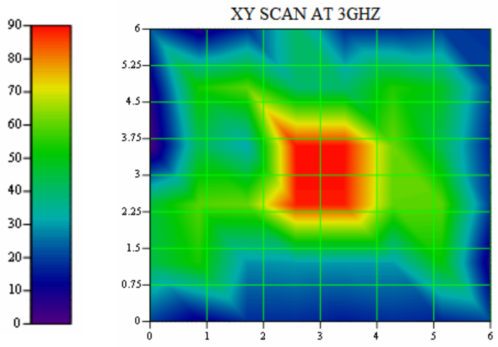

Figure 8. Surface (2D) scan of water phantom at 3 GHz

Discussion

In the framework of the present research, the experimental feasibility of a prototype focused microwave imaging device, consisting of a conducting wall ellipsoidal cavity with a multi-frequency microwave radiometric system as receiver operating in the range of 1.0-3.1GHz, is illustrated.

Phantom experiments with the multifrequency receiver confirm and substantiate theory and previous experimental results. Implementation of the MiRaIs in a significant number of experiments using phantoms and in humans with the use of two single frequency radiometric receivers (1.5GHz and 3.5GHz) have shown promising results concerning temperature and conductivity imaging. Similar experiments involving human subjects will be performed in the near future using the newly designed multifrequency sensitive radiometric receiver.

Conclusion

The MiRaIS being possibly a prototype of a future diagnostic totally passive tool could potentially become a useful clinical complement to conventional brain imaging techniques. Further and in-depth research is required in order to explore its clinical value.

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