

## A Review on Microwave Tomography System

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Available online 30 December 2025

### ABSTRACT

Microwave Tomography (MWT) is an emerging imaging modality that utilizes electromagnetic radiation in the microwave frequency range to reconstruct the dielectric properties of an object. This paper reviews the fundamental principles, system construction, and diverse applications of MWT, particularly in the medical, industrial, and civil engineering fields. Unlike X-ray or CT scans, MWT offers a non-invasive, non-ionizing, and cost-effective solution for imaging soft tissues, making it highly suitable for early breast cancer detection, brain stroke diagnosis, and myocardial infarction imaging. The system operates by measuring the scattering of microwave signals caused by variations in permittivity and conductivity within the target. The review also highlights MWT's utility in hydrogeophysics for soil moisture analysis and in civil engineering for non-destructive testing of concrete structures. Despite challenges in image reconstruction due to diffraction and scattering, advancements in inverse scattering algorithms continue to improve spatial resolution and diagnostic accuracy.

**Keywords:** Microwave tomography system, image reconstruction, dielectric properties, inverse scattering

### 1. Introduction

Microwave Tomography System or MWT is very popular for medical applications. Microwaves imaging technique for medical purpose has been starting in early 80's and the famous resehers in this era are Larsen and Jacobi.[1]This type of tomography system produces a non invasive measurement system and non hazardous ionizing radiation. This happened because the energy of photons is small enough to avoid the ionization effects. [2] That is why this tomography system widely uses in medical field. Microwave tomography system is an imaging modality that uses electromagnetic radiation to reconstruct a quantitative image of the dielectric properties of an object of interest. [3]Microwave tomography system (MWT) can differentiate the dielectric properties by depending on the ion concentration and mobility, concentration of free water and bound water and tissues temperature. [2]Most of the microwave tomography system used inverse scattering algorithm for solving image reconstruction problem. [4]Research on microwave tomography system is going on decade by decade because this tomography method give many advantages such as low cost and portable compared to MRI and X-Ray, not exposed with hazardous ionizing radiation, capable to image bulk electrical properties as a feature of tissues, no need any contrast agent to enhanced the capability of capturing images, and suitable for monitoring the disease at early stage. [4]

As above mention, imaged reconstruction of microwave tomography system is focusing on permittivity and conductivity. That the reason why this tomography system mostly applied for geophysical and biological field because soft tissues is highly in dielectric, permittivity and conductivity contrast. Due to the permittivity and conductivity that is inhomogenous, it will cause high scattering of image and will result a nonlinear inverse problem. [5]Microwave tomography system has the ability to differentiate the normal and abnormal tissues based on the dielectric properties. This tomography system is very useful for breast cancer detection, diagnostic lung cancer, brain imaging and cardiac imaging process too. [6]

While for geophysics filed, this microwave tomography system is widely used for estimating the thickness of dielectric slabs. This electromagnetic spectrum can be used to monitor the thickness variation in ceramic, thermal

barrier and concrete pavements and refractory walls. [7] Actually, microwave signal is very sensitive to boundaries at dielectric slabs because the source of microwave spectrum will be reflected to the transmitter upon incident of its boundaries and it will reflect back microwave signal coherently and will use estimation spectrum techniques to determine the locations of the slabs interfaces. [7] Estimation spectrum technique has the capability to detect two reflection spaced by the time it takes the signal to travel between the interfaces. It also can resolve the time delay between the interfaces. For our information, the resolution in estimating the delay time is proportional to the bandwidth of the transmitted signal where the higher the bandwidth the higher the resolution. [7]

## 2. Basic Principle of Microwave Tomography System

The basic principal of microwave tomography system is based on the frequency of microwave wavelength. This tomography method use the electromagnetic radiation in the frequency range of few hundred megahertz to a few gigahertz's to quantitatively reconstruct the complex permittivity of the object imaged.[8] Microwave tomography using low power electromagnetic radiation with wavelength in the centimetre range for reconstructing centimetre sized details in the dielectric and conductivity properties of tissues cells.[9] This tomography method is used for medical purpose because it is low cost, non-ionizing radiation and has the ability to image the large electromagnetic properties of tissues. [8] This tomography method still has the disadvantages. One of it is, this tomography method wave radiation easily being absorb or shielded by the biological tissues. This usually occurred when the receivers and transmitter are place near to each other. Some researchers from Russia advise to use double used of radiation focusing. [10] For microwaves tomography system, an inverse scattering algorithm is use for image reconstruction to reconstruct the shape, location, and dielectric properties of the object of interest from the measured fields. [11]

Material can be characterized based on the dielectric permittivity and magnetic permeability. The knowledge of complex permittivity make it possible to access different quantities of material compositions, water contents, blood flow rate, and temperature. Microwave tomography system consists of two type of imaging technique; narrow pulse signal and wideband signal.[12] The interaction between microwave spectrum and material is very complicated process. For this source of electromagnetic wave, diffraction process is take part when the wave hits the materials. At previous stage, this microwave tomography system faced with certain problem that happened cause by diffraction mechanism. The problems are the impossibility of producing well collimated and narrow beams with diameter less than the wavelength, the limitation of the spatial resolution to one half of a wavelength resulting from imperfect focusing and multipath interaction such edge effect and multiple scattering .[12] For microwave tomography system, the imaging process can be divided into two; quantitative and qualitative.

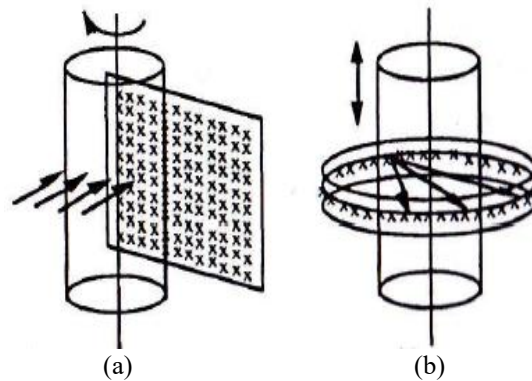
There are two different microwave imaging approaches; single frequency technique and swept frequency technique. For single frequency technique, experiments can conduct in two ways; planar situation and circular situation as Figure 1 shows two different arrangement of transmitter and receiver at same shape of pipeline. Figure 1 (a) shows the planar situations and Figure 1(b) shows circular situation. The concept it is apply is based on the transmitting and receiving data in one straight way. For an example, when one antenna transmitting electromagnetic wave, another receiver that placed in front of the transmitter will receive the data. For swept frequency technique, it is directly used the data from microwave transmission in X-Ray tomographics reconstruction algorithm. [12].

To enhance the imaged quality, multi viewing is suggested by rotating the targets or the sensors. Figure 2 shows the schematic diagram for microwave tomography system that consists of three main parts. [2] First part is measurement chamber antenna. This part consists of certain number of receivers and emitters. It is suggested to do double layer antenna to improve the cross polarization performances. [3] Second part is the multiplexer to switch the receiver and transmitter antenna. All the data captured by receiver will send to the computer by using data acquisition system.

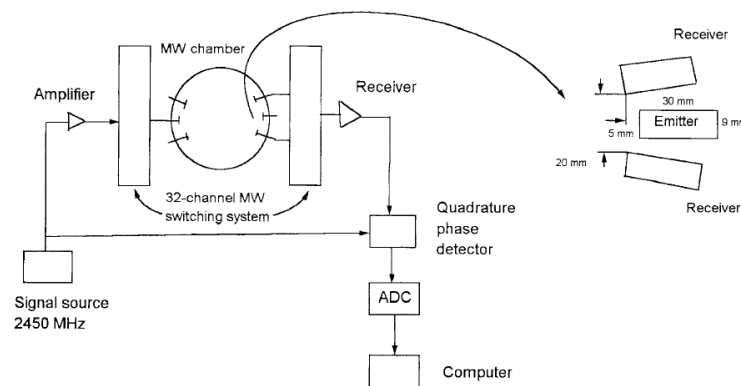
Data acquisition system consists of two approaches in obtaining data; direct method and indirect method. For direct method, it measure receive voltage from using antenna. Probes is not included. The receiving antenna usually located at the point where the electromagnetic fields need to be measured. There are many types of receiving antenna such as array of co resident receiving antenna, monopoles, open ended wave guide and double layered Vivaldi antenna. For indirect method, it measured the voltage output at the probe at the same distance from receiving antenna located. It is known as modulated scattered technique. From the research observation, to increase the number of observation, is by increasing the numbers of probes. [3] For image reconstruction using indirect method, each measurement at a probe location is performed by changing of the impedance of those probes. When probe active, remaining probe are kept open so they remain invisible to electromagnetic fields. The changes of impedance will cause changes in voltages. To measure scattered field, total field for object of interest and the incident field with object interest absent in the measurement chamber are collected. [3]

While for direct approach, to increase the number of observation, more antenna need to be apply to the co resident antenna array but it is difficult and time consuming. This will result the increasing of mutual coupling. For information, microwave tomography system usually faced with problems on estimating the variation of dielectrics properties and it is suggested to utilize the wideband microwave signals and high resolution spectrum estimation technique which require either a very narrow pulses or wider band signals based on the requirement of measurement process [7]

Errors for image reconstruction sometimes happen because of instrumentation error and polarization error. Instrumentation errors sometimes cause by time varying cables and room temperature. For polarizations error the antenna not be able to differentiate the differentiation polarization of field within the chamber. The ways to solve above problems are by repeating the measurement and perform the measurement within short period. [3]High values close to the antenna and very low away from them translate too poor system matrix and high ill conditioned inverse problem too. In a way to solve this problem, a robust iterative perturbation technique is suggested. [5]



**Figure 1.** Figure (a) show planar arrangement of sensors and figure (b) shows in circular arrangement of sensors



**Figure 2.** Schematic diagram for microwave tomography system

### 3. Applications

Microwave tomography system is another choice of tomography methods that applied in medical and process industries. For microwave imaging technique, it is believe that this source of electromagnetic wave can detect the organ movement and changes in water contents via its dielectric properties. [13]Surely, this type of tomography system is using microwave spectrum in detecting objects. It is based on the contrast in dielectric properties of materials. [14]This type of tomography system can be categorized as non invasive tomography techniques and very suitable for soft tissues image reconstruction.

By using microwave tomography system, biological tissues can be differentiate based on dielectric properties. For high contrast of dielectric shows the muscle tissues and low contrast of dielectric show the fat and bones. [14]This microwave tomography can provide information about the physiological state of tissues as well as the anatomical structure of an organ too.

This tomography system can provide a two dimensional or three dimensional of image reconstruction. [15]For three dimensional of image reconstruction, microwave tomography method use at the frequency value of 1GHz is suggested.[16]A researcher also has revealed the ability of this tomography system to construct an image of three dimensional of complex internal structures of heart including the right and left hand side. [17]

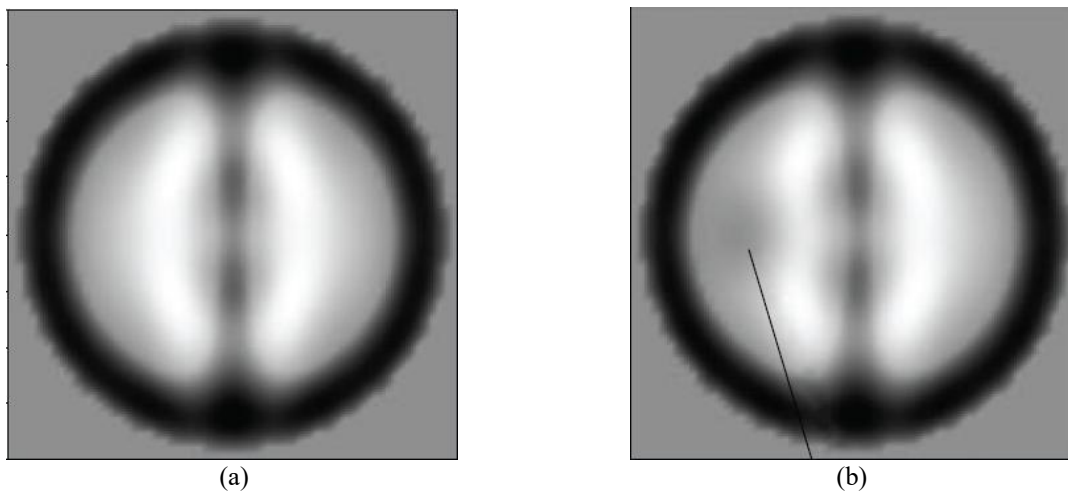
It can be conclude that microwave tomography system can be used for monitoring arterial wall motion, respiratory movement, ventricular volume change and movement. This type of tomography system promised to give high quality and high contrast of image reconstruction. [18]

### 3.1 Microwave Tomography System for Brain Imaging

Brain imaging process is very important to monitor the constant of blood flow. Stroke or brain attack can be recognized through brain imaging process when the image reconstruction shows the abnormal blood flow in patients. Blood carries oxygen and the process of blood flow to carry the oxygen into brain and carry the waste are very important to investigate. If the flow is stuck, it can lead to the death of patient. [19]Brain imaging technique is very important to reveal the pathophysiological changes in brain tissues that result by the strokes. [20]Previously, the imaging method that widely used for brain imaging image are computed tomography system (CT), Positron Emission Tomography (PET) system, and Magnetic Resonance Imaging (MRI). Unfortunately, all the equipment mention above high in cost. Microwave tomography system has been introduced in biological imaging process recently. This method is low cost, safe and portable. This type of tomography can differentiate the malignancies, blood supply, hypoxia and chronic infarction through the variety values of dielectric properties. [21]Muscle tissues and bone can be differentiating through the high water contents that carry high dielectric properties.

In 1982, Larsen and Jacobi present very detail image of anatomical that clearly visible and specific dependence of the dielectric constant to factors such as blood flow rate and temperature. According to Larsen and Jacobi, due to the wavelength contraction, the spatial resolution obtained in water approximately nine times better than air.

Microwave tomography imaging technique can differentiate between the internal brain and skull through the different dielectric properties between two substances. Low dielectric contrast will show the skull while high dielectric contrast that carries blood flow shows the brain. To analysis the brain which have brain attack or stroke symptoms, the image for normal brain is needed to make a comparison. Patient having stroke will wear a circular ring on their head. This circular ring contents the transmitter and receiver antennas for microwave sources. Normally, more transmitters and receivers used can promise high quality of image reconstruction. This microwave sources is not harm for human life. For brain imaging using microwave sources, they usually apply frequencies between 0.5GHz to 2.0GHz. While for image reconstruction they will use direct problem solver. From the image result, the area of stroke can be easily detected when there are dielectric properties distribution is inhomogeneity. [21]Figure 3 below shows the two different brain images. For Figure 3(a), it shows the normal brain that dielectric properties are distributed homogenous. While for Figure 3(b), it shows the abnormal brain that may result the stroke because the distribution of dielectric properties is inhomogeneity.



**Figure 3.** Two different brain images where for figure 3(a), shows normal brain and figure 3(b) shows abnormal brain

### 3.2 Microwave Tomography System for Breast Cancer Detection

For breast cancer imaging technique, X-Ray mammography is widely used because of it high accuracy of image reconstruction. Unfortunately, this application is not safe because patient easily being exposed by ionization radiation that can harm patient if they are being exposed for many times. [22]X-Ray mammography being reported as a painful system for breast imaging technique because it is uncomfortable for patient because the breast needs to be compressed for screening purpose. [23][24]Then, to overcome this problem another method that known as Magnetic Resonance Imaging (MRI) is proposed. But the cost is very expensive. [25]That is the reason why microwave tomography technique is being developed day by day to produce a comfortable system for breast cancer patients. Many research have supported the idea that microwave tomography system has the capability to detect breast cancer according to the detection of different dielectric properties of normal tissues and malignant breast tissues. [26][27][28]For microwave tomography system, it is not give high spatial resolution of image reconstruction that produced by X-Ray mammography. This tomography method offer high contrast in image reconstruction that based on the water content,

blood flow rate and temperature. But, the advantages of using microwave tomography techniques are; patients no more feel uncomfortable because this application is non invasive and non intrusive, no ionizing radiation and low cost. [29] Due to the development of microwave imaging technique for breast cancer detection, two famous methods have been proposed. There are known as microwave tomography system and Ultra Wide Band Microwave Radar. [30][31] Both instruments using microwave signals.

### 3.3 Microwave Tomography System for Myocardial Infarction Imaging

Myocardial Infarction imaging process related with the heart and large vessel anatomy images process. Microwave tomography system is believed to produce an image of blood flow and metabolism of the myocardial tissues. The changes of dielectric properties in myocardial tissues are very important for microwave imaging technique. This tomography system has the ability to differentiate the normal tissues and injuries tissues based on the dielectric properties distribution. [32] According to Serguei, optimal microwave frequencies for biological object scale are within 0.9GHz to 1.2 GHz. To obtain a three dimensional images of heart, he suggested for 1GHz frequency of microwave spectrum. [32]

### 3.4 Microwave Tomography System for Hydrogeophysics

Microwave tomography system is suggested to use for monitoring the soils contents for hydrogeophysics fields. Microwave tomography method can be considered as non invasive technique for monitoring the dielectric permittivity of the soil using ground penetrating radar. [33][34] This system can be used for measured the dielectric permittivity in hydrology and underground. That why it is known as hydrogeophysics fields. This application is needed to measure the water content in soil. Besides that, it also provides the information of the permittivity of soil. This information is very important for soil further analysis. [33] According to Francesco Soldoveiri, microwave tomographic approaches consist of three subdivisions. First subdivision is known as electromagnetic scattering inverse problem. This problem must be formulated into two dimensions of geometry and in frequency domain. Second subdivision is known as numerical method and inverse method. Third subdivision is needed to move from the total field in the time domain to the scattered in the frequency domain.

Microwave tomography systems can be apply for capturing subsurface images that contents different dielectric properties. To enhanced the image reconstruction for subsurface sensing system, multiresolution method is being proposed. This multiresolution method consists of another two methods. First known as fix multiresolution where detail of the object can be observe when it is close to the surface and become invisible when it is deeply buried. For second method is known as adaptive multiresolution [35]

Microwave tomography system is capable to capture an image of buried objects. This can happened because microwave spectrum can penetrate through thick wall too. This application is very important for non destructive testing methods. In research related with microwave tomography system for detecting buried objects, it involved two different algorithms. First it deals with qualitative algorithm based on diffraction tomography for detecting the buried object. Secondly, it deals with quantitative algorithm for reconstructing the complex permittivity profile of the object. This non destructive testing application is very important for geophysical, civil engineering, military, or humanitarian applications for detection the voids, pipes, cables and civil engineering structures. [36]

### 3.5 Microwave Tomography System for Civil Engineering

Microwave signal is very suitable for penetrating through opaque media and it can be used for non invasive testing and measurement. [37] Microwave signals have the ability to penetrate through non metallic wall. [38] This can be proved by the cell phones, hand held phone and wireless router which can operate successfully through the building. [39] The concept that microwave tomography system applied still the same. It will measure the distribution of dielectric behind the wall. From the measurement of dielectric value, image reconstruction of the object behind the wall may be determined. By using this tomography system with the suitable of frequency wavelength, the cross sectional imaging of dielectric and metal objects on the other side of concrete wall or concrete block can be image. [40] Actually, microwave tomography system is very important for civil engineering to monitor or detect object location within the wall and checking for concrete structure. This tomography system has high cross range resolution, low power consumption, not expensive, and high speed. Recently, there are many development of microwave tomography system for civil engineering purpose because the size of the equipment can be small and portable. There are many available microwave tomography systems in small sized and light weight and contains with desktop or portable computer equipped with data acquisition board. Other examples for this application are known as scanning control block and dielectric microwave antenna probe. [40]

### 3.6 Microwave Tomography System for Industrial Applications

Microwave tomography system can be applied as inspection instrument in industries. Microwave signals can penetrate through thick wall and absolutely this advantage make microwave tomography system valuable for non destructive monitoring system. Microwave tomography system can monitor the reflection or transmission coefficient with linear sensor that allowed the information on the internal structure or composition of product being investigated.

[12] This type of tomography system offer no thermal and ionizing effects and non invasive or non intrusive instrument.

#### 4. Image Reconstruction

For image reconstruction, inverse algorithm is used. But, researchers will deal with challenges because inverse algorithm related with linear or nonlinear problems and this sometimes can cause false solutions. [41] Besides that, the image reconstruction also difficult to obtain using non linear problem because not only the parameter are unknown; the fields' distribution are unknown too. [42] A researcher from United State in 2003 has introduced iterative nonlinear inversion method or contrast source inversion method that using multiplicative regulation to be an efficient and accurate inversion technique. [42] Other method which is known as Lavenberg Marquardt method is being introduced by researchers for complex permittivity reconstruction for microwave imaging technique. This reconstruction method refers to quantitative reconstruction of the dielectric and conductive property distributions of biological objects. [43]

With this type of tomography system, various types of image reconstruction algorithm can be used such as iterative reconstruction and linear back projection algorithm. For microwave tomography method, the quality of image reconstruction is based on the numbers of receivers, the accuracy of scattered field measurement, and the dielectric contrast. [44][45]

Microwave tomography system can be produce in two dimensional images and three dimensional images too. Usually, for producing three dimensional images, the frequency suggested is 2.4GHz. Three dimensional images always give high quality of image reconstruction. The detail of dielectric properties tissues can be analysis deeply in three dimensional image reconstructions. [46] Three dimensional images are very important in biological field for the requirement of research. To obtain two dimensional images, Newton method is used [47] and inverse problem for Maxwell equation is apply. [48] For three dimensional images, it usually used gradient iterative method [49] and Hemholtz equation. [50]

#### 5. Conclusion

As a conclusion, this microwaves tomography method is another non invasive and non intrusive tomography method that can be applied for medical and process industries monitoring purpose. This tomography method is one of the methods that using spectrum wavelength and it is non ionizing radiation and safe for human and other objects. But this tomography method has it limitation based on the dielectric contrast and researchers have introduced variety methods and approaches to deals with these problems. Beside that, researchers also introduces many algorithm to help enhanced the quality of image reconstruction. The developing of microwave tomography system has help tomography field become one of important method that widely used especially for non destructing testing (NDT) methods. Low energy consumption and low cost have been attract specialist in industries to apply this methods for monitoring purpose. Besides that, in medical filed, this system has been recognized as a comfortable method for patients that suffer from various diseases.

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