NOVEL CHANNEL IMPULSE RESPONSE EQUATIONS OF NORMAL AND MALIGNANT SKIN AT HIGH FREQUENCY MM-WAVE BAND

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ABSTRACT*—In this paper, by using the permittivity and conductivity values of normal and high water content malign skin tissues for 50-75 GHz mm-wave band, we have proposed new model equations for the channel impulse response viz by evaluating the scattering matrix for human skin. The equations are separate for normal and malignant skin tissue. Developed model equations have a maximum error of 7.9% and 11.3% of the channel impulse response of normal and malignant skin respectively between analytical model and experimental results. The results presented here will serve as exploratory foundation for intriguing more pronounced steps in the skin cancer research*.

Key Words—Electric permittivity, electric conductivity, malignant, mm-wave, cancer, skin

I. INTRODUCTION

Cancer is a hysterical propagation of abnormal cells that target and invade neighbouring non cancer normal cells. Site of the abnormal cells define the type of cancer in the patient.

The major part of our human body is skin. Skin cancer is spreading fast among the people. The three common types of skin cancer are ***melanoma*** (begins in pigment cells "melanocytes"), ***basal cell skin cancer*** (begin is basal cells, usually occurs in places exposed to sun) and ***squamous cell skin cancer*** (most common type and usually occurs in places not exposed to sun like legs or feet's). The main risk factor for skin cancer melanoma and basal cell is exposure to sunlight (UV radiation) in terms of severe or blistering sunburns, lifetime sun exposure, tanning, personal history and family history. Malignant melanoma arises when melanocytes start to grow uncontrollably, due to a specific mutation in the DNA structure. Most cases of cell mutation leads to programmed cell death (apoptosis) except when a very small set of genes, called oncogenes are mutated, in which case the cell can start to proliferate uncontrollably (cancer). If the cancer is left untreated it can start to spread via blood and lymph vessels to the lymph nodes, other organs or other distant tissues (metastasis). The transformation from a benign into a malignant melanocyte is not yet fully understood, but sun exposure especially in early childhood and sunburns in people with fair/white skin seem to be important risk factors, which clearly is reflected in the melanoma incidence and mortality in the following section. Some other risk factors that need to be taken into account are family history of melanoma, previous melanoma, large number of melanocytic (pigmented) nevi, skin color/type, genetic disposition as well as other environmental factors [1-6]. Reports from World Health Organization (WHO) stated that the occurrence of non-melanoma and melanoma skin cancers has an escalating trend for the previous years. At present, from a rough estimate and average of two to three million skin cancer cases arise worldwide annually. Such a big count demands steps to be adapted to lessen skin cancer.

II. PROBLEM STATEMENT

There are several techniques used to investigate the occurrence and incidence of skin cancer. Among them, the reflection measurements of human tissues have shown great potential. Reflection measurements of organic tissues at high frequencies have revealed a noteworthy distinction between the behavior by which electromagnetic waves reflect back from normal and cancer containing tissues. This makes these abnormal cells noticeable. In other words acquaintance of channel impulse response in terms of reflection coefficient or S_{11} parameter is useful for detection of malignant lesions..

For finding the reflection coefficient S_{11} channel impulse response, we need to know the electric permittivity and conductivity values of skin tissues at working frequency, i.e. in our case at mm-wave frequencies. This requires the mathematical modeling of human skin in terms of its dielectric properties. A number of research studies have been conducted but prominent particular to this study are briefed here. Gabriel *et al.* [7] determined the permittivity and conductivity results of many organic tissues from 20 GHz to 110 GHz using extrapolation founded on a Cole-Cole equation. In [8] modeling by Debye equation (for single relaxtion) was inspected by approximating it on with S_{11} results of normal human skin at microwave millimeter set of frequencies. Chahat *et al.* [9] considered the real and imaginary values of permittivity of the skin for forearm and wrist by means of unrestricted coaxial probe for the frequencies of 55-66 GHz. But none of these researches have provided an analytical mathematical equation that could be used to predict or find S_{11} or channel impulse response of skin.

III. RESEARCH METHADOLOGY

Our research methodology consists of the following steps:

- Obtain dielectric properties at millimeter wave frequencies from the experimental work done in [10]
- Obtained experimental S_{11} values from [10].
- Developed analytical model for multiple reflections as inside human tissues, i.e. in our case is human skin
- Determine the error in S_{11} between analytical model and experimental results in [10]
- Remove the errors and finalize the results

IV. DATA AND MATERIAL

Skin tumors grow at the upper layers and subsequently expand deeper. The dielectric values for normal skin as well as malignant skin as obtained in [10] are reproduced here:

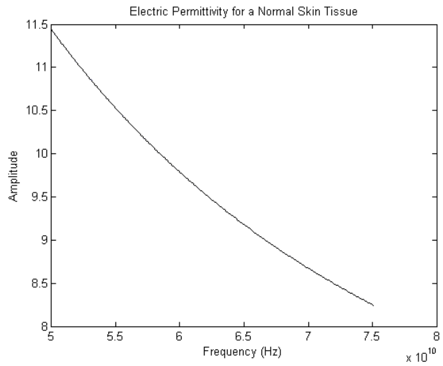

Figure. 1 Electric permittivity for a normal skin (50-75 GHz)

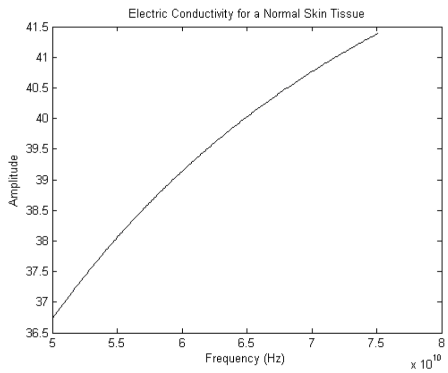

Figure. 2 Electric Conductivity for a normal skin (50-75 GHz)

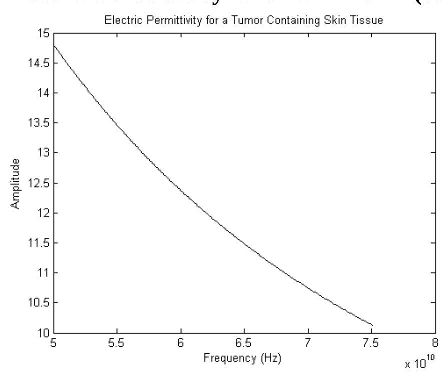

Figure. 3 Electric permittivity for a malignant skin (50-75 GHz)

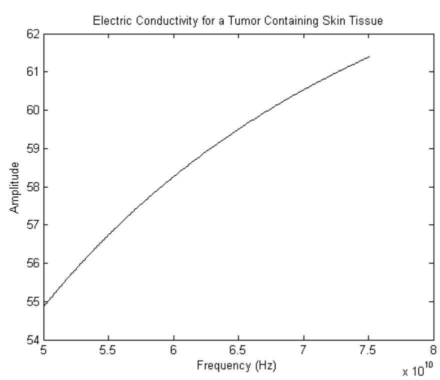

Figure. 4 Electric conductivity for a malignant skin (50-75 Ghz)

In these plots normal or healthy skin is considered with water content percentage 65% and malignant skin is considered with water content percentage of 81% and a 2.6 mm diameter single tumor as taken in [10]

VI. MATHEMATICAL MODELING

In order to derive the analytical expressions for transmission and reflection coefficients, we considered the scenario shown in Figure 5. This is divided in three regions. They are '0', '1' and '0' for the incident, channel and forward transmitted regions respectively. Here '0' indicates the air region and '1' indicates the body tissue medium. These regions are separated by boundaries named A and B. Region 0 is the region where incident signal comes, and incident signal $\psi_{inc} = 1$. It is then forward propagated and reflected as shown in the Figure 5. with respect to the reflection coefficients and transmission coefficients defined at the boundaries A and B. Important definitions are as follows,

r_{01} = reflection coefficient at interface A between regions 0 & 1.
r_{10} = reflection coefficient at interface B between regions 1 & 0.
t_{01} = transmission coefficient at interface A between regions 0 & 1.
t_{10} = transmission coefficient at interface B between regions 1 & 0.
k_1 = propagation constant for region 1 with zero attenuation.
k_0 = propagation constant for region 0 with zero attenuation.
a = thickness of channel / region 1

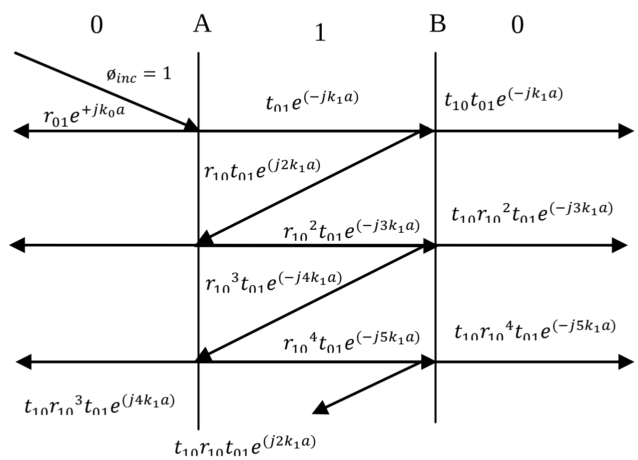

Figure 5: Wave functions resulting from the incident ψ signal by successive transmission and reflection

Total transmitted signal ψ_{trans} comes out can be defined as,

$$\psi_{trans} = t_{10}t_{01}e^{(-jk_1a)} + t_{10}r_{10}{}^2t_{01}e^{(-j3k_1a)} + t_{10}r_{10}{}^4t_{01}e^{(-j5k_1a)} + \cdots \quad (1)$$

Simplifying Equation (1), we have,

$$\psi_{trans} = t_{10}t_{01}e^{(-jk_1a)}\left[1 + r_{10}{}^2e^{(-j2k_1a)} + r_{10}{}^4e^{(-j2k_1a)} + \cdots\right] \quad (2)$$

By applying summation on the geometric series inside the braces in Equation (2) and using the definition, that $r_{10} = -r_{01}$, we have,

$$\psi_{trans} = \frac{t_{10}t_{01}e^{(-jk_1a)}}{[1 - r_{01}{}^2e^{(-j2k_1a)}]} \quad (3)$$

We know that,

$$k_0 = \left(\frac{\omega}{c_0}\right) \quad (4)$$

$$k_1 = \sqrt{\varepsilon'\left(\frac{\omega}{c_0}\right)^2 - j\omega\mu_0\sigma} \quad (5)$$

nd refractive index n and propagation constants k are related by,

$$n = \frac{c}{\omega}k \qquad (6)$$

where c is the speed of light or EM waves in the vacuum, and ω is angular frequency of EM wave and k is the propagation constant for any medium.

Propagation constant and reflection coefficient at the boundaries are defined by,

$$\left.t_{10} = \frac{2n_1}{(n_1+n_0)}, t_{01} = \frac{2n_0}{(n_0+n_1)}, r_{01} = \frac{(n_0-n_1)}{(n_0+n_1)}\right\} (7)$$

Taking $\frac{c}{\omega}$ as constant at a particular frequency and using we have,

$$t_{10} = \frac{2\frac{c}{\omega}k_1}{(\frac{c}{\omega}k_{1_1}+\frac{c}{\omega}k_0)}, t_{01} = \frac{2\frac{c}{\omega}k_0}{(\frac{c}{\omega}k_{1_1}+\frac{c}{\omega}k_0)}, r_{01} = \frac{(\frac{c}{\omega}k_0-\frac{c}{\omega}k_1)}{(\frac{c}{\omega}k_0+\frac{c}{\omega}k_1)}$$

which after simplification becomes,

$$\left.t_{10} = \frac{2k_1}{(k_1+k_0)}, t_{01} = \frac{2k_0}{(k_0+k_1)}, r_{01} = \frac{(k_0-k_1)}{(k_0+k_1)}\right\} (8)$$

Putting the values of t_{10}, t_{01} and r_{01} in Equation (3) we have after simplification, as,

$$\psi_{trans} = \frac{4k_1k_0e^{(-jk_1a)}}{e^{(-j2k_1a)}[e^{(j2k_1a)}(k_0+k_1)^2-(k_0-k_1)^2]}$$

or ,

$$\psi_{trans} = \frac{4k_1k_0e^{(jk_1a)}}{[e^{(j2k_1a)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (9)$$

Since the incident signal $\psi_{inc} = 1$, then Equation (9) is the transmission coefficient as, transmission coefficient, T, is,

$$T = \frac{\psi_{trans}}{\psi_{inc}}$$

In general, for any other incident signal with phase term defined with $\psi_{inc} = e^{(-jk_0a)}$, then transmission coefficient of Equation (3) becomes,

$$T = \frac{4k_1k_0e^{(jk_1a)}e^{(jk_0a)}}{[e^{(j2k_1a)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (10)$$

If the medium in region 1 is symmetric then the thickness of this region can be considered as $a = 2t$, then Equation (10) becomes,

$$T = \frac{4k_1k_0e^{j2t(k_1+k_0)}}{[e^{(j4k_1t)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (11)$$

In a similar manner the (as written in Equation 11) received signal , ψ_{rec} can be followed by the final version as in Equation (12)

$$\psi_{rec} = \frac{r_{01}-r_{01}e^{(j2k_1a)}}{[1-r_{01}{}^2e^{(j2k_1a)}]} \qquad (12)$$

$$\psi_{rec} = \frac{(k_0{}^2-k_1{}^2)(e^{j2k_1a}-1)}{[e^{(j2k_1a)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (13)$$

Since the incident signal $\psi_{inc} = 1$, then Equation 13 is the reflection coefficient, because the reflection coefficient, Γ, is ,

$$\Gamma = \frac{\psi_{rec}}{\psi_{inc}} \qquad (14)$$

For any other incident signal with phase $\psi_{inc} = e^{(-jk_0a)}$, the reflection coefficient in Equation (14) becomes,

$$\Gamma = \frac{(k_0{}^2-k_1{}^2)(e^{jk_0a})(e^{j2k_1a}-1)}{[e^{(j2k_1a)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (15)$$

Followed by for a symmetric medium Equation (15) becomes,

$$\Gamma = \frac{(k_0{}^2-k_1{}^2)(e^{j2k_0t})(e^{j4k_1t}-1)}{[e^{(j4k_1t)}(k_0+k_1)^2-(k_0-k_1)^2]} \qquad (16)$$

V. RESULTS AND DISCUSSION

In order to determine the skin properties using high frequency radars, we prefer to use reflection coefficient i.e. S_{11} values than transmission coefficient or S_{12} values. Therefore in this paper we have also estimated the channel impulse response for reflection coefficient i.e. S_{11} of the normal and tumor containing skin. We used Equation (16) and compared our model with the experimental results for normal and malignant skin [10]. Results obtained are shown in Figure 6 and Figure 7 respectively.

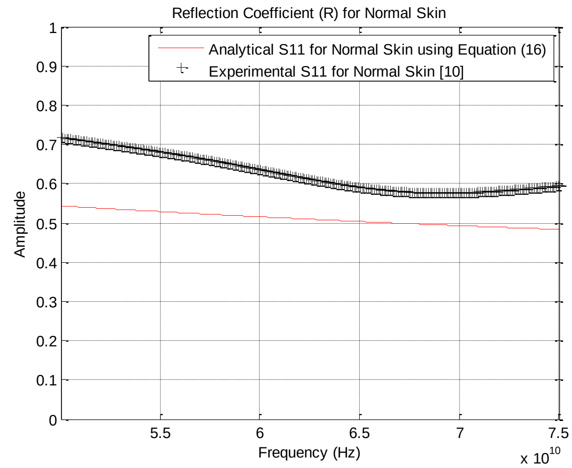

Figure 6. Reflection coefficient of normal skin (Analytical and experimental results)

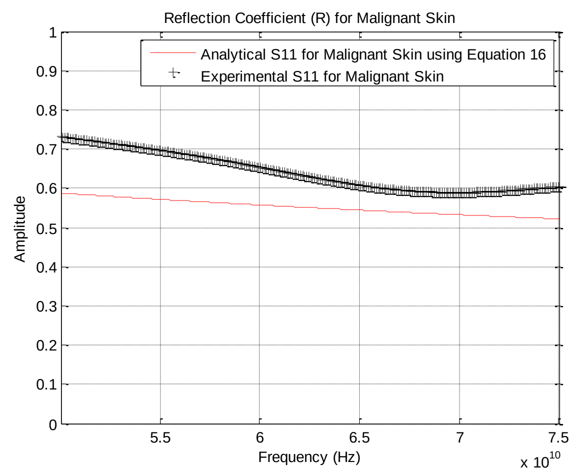

Figure 7. Reflection coefficient of malignant skin (Analytical and experimental results)

On comparing analytical and experimental results as in Figure 6 and Figure 7 we found that maximum squared error found is 0.0303 (3.03%) and 0.0208 (2.08%) respectively. We also noted that our analytical models are not following the non linearity in the experimental results. Therefore we need some alternative way to remove or reduce these ambiguities in our model in Equation (22). As a first attempt we used ordinary least square regression (OLS).

Ordinary Least Square Regression

At first we used OLS regression modeling to reduce the errors. Statistical modeling uses ordinary least squares (OLS) or linear least square method in a linear regression model to determine the unknown parameters. OLS regression technique has been used previously for microwave UWB frequency band to model human tissues as in [11]. The objective of estimation is to minimize the distance between observed responses in some arbitrary dataset to the responses predicted by linear approximation of data. This can be observed visually as the sum of vertical distances between each data point in the set and corresponding point on the regression line. The model fits data set better if the difference is small. Suppose a data set of n observations where y_i is the output dependent variable and independent variables or predictors are x_i. The relation between response variable and independent input variables is linear for linear regression model, as shown below:-

$$y_i = x_i^T \beta + \varepsilon_i \qquad (17)$$

here ε_i's are the error in the model and β are unkown coefficients to design. This model can also be written in matrix notation as

$$y = X\beta + \varepsilon \qquad (18)$$

Sum of Square Residuals or SSR is quantifies the overall model fit, given as

$$SSR = (y - X\beta)^T (y - X\beta) \qquad (19)$$

Here T is the indicator of transpose of a matrix. The value of β which gives the least value of Equation(19) is termed as OLS estimator for $\widehat{\beta}$. Value $\widehat{\beta}$ can be found as

$$\widehat{\beta} = (X^T X)^{-1} X^T y \qquad (20)$$

Once β is obtained, estimated or predicted measures from the regression are given as,

$$\hat{y} = X\widehat{\beta} \qquad (21)$$

Or

$$\hat{y} = X\{(X^T X)^{-1} X^T y\} \qquad (22)$$

For removing the maximum errors and properly estimating the channel impulse response of the normal and tumor containing skin we applied OLS regression modeling on Equation (16) using Equation (22). The results obtained are stated in Equations (23) and (24) as new reflection coefficients as S_{11}^N and S_{11}^T for normal and malignant skin respectively.

$$S_{11}^{N} = \frac{\left(\frac{\omega}{c_0^2} - \varepsilon'\frac{\omega}{c_0^2} + j\mu_0\sigma\right)\left(e^{2j\frac{\omega}{c_0}t}\right)\left(e^{4jt\sqrt{\varepsilon'\frac{\omega^2}{c_0^2} - j\omega\mu_0\sigma}} - 1\right) + 1.2293\left[\left\{\left(e^{4jt\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}}\right)\left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} + \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right\} - \left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} - \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right]}{\left\{\left(e^{4jt\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}}\right)\left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} + \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right\} - \left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} - \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)} \qquad (23)$$

$$S_{11}^{T} = \frac{\left(\frac{\text{ù}}{c_0^2} - \text{å}'\frac{\text{ù}}{c_0^2} + j\text{ì}_0\text{ó}\right)\left(e^{2j\frac{\text{ù}}{c_0}t}\right)\left(e^{4jt\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}} - 1\right) + 1.1646\left[\left\{\left(e^{4jt\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}}\right)\left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} + \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right\} - \left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} - \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right]}{\left\{\left(e^{4jt\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}}\right)\left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} + \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)\right\} - \left(\frac{\text{ù}}{c_0^2} + \text{å}'\frac{\text{ù}}{c_0^2} - j\text{ì}_0\text{ó} - \frac{2}{c_0}\sqrt{\text{å}'\frac{\text{ù}^2}{c_0^2} - j\text{ùì}_0\text{ó}}\right)} \qquad (24)$$

The analytical modeled values of channel impulse response for the normal skin and malignant skin using Equation 16 along with estimated compensation proposed by our method through OLS using Equations 23 and 24 are shown in Figure 8 and Figure 9 below.

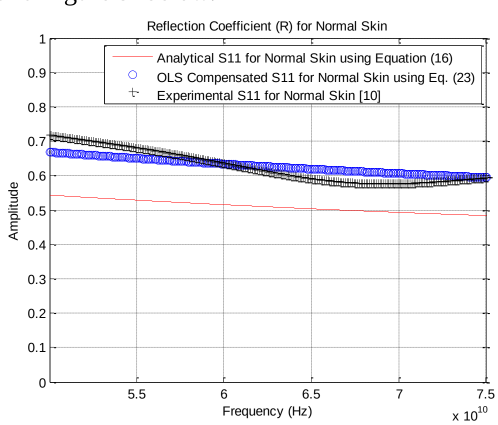

Figure 8. Reflection coefficient of normal skin (OLS compensated, analytical and experimental results)

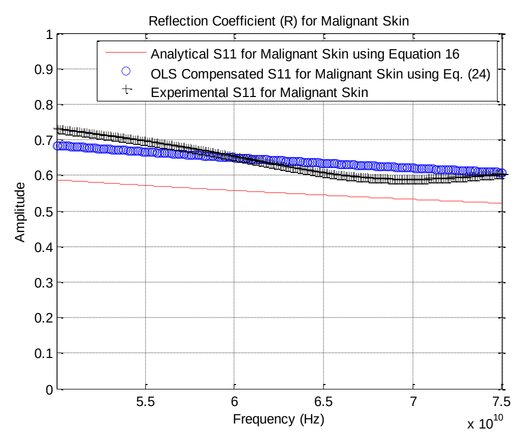

Figure 9. Reflection coefficient of malignant skin (OLS compensated, analytical and experimental results)

On comparing analytical and experimental results as in Figure 8 and Figure 9 we found that maximum squared error found is 0.0024 (0.24%) and 0.0023 (0.23%) respectively. That is Equations (23) and (24) have improved the analytical model in Equation (16) by lowering the maximum error in comparison to analytical results to 7.9% and 11.3% for normal and malignant skin respectively.

VI. CONCLUSION

In this paper we have successfully formulated the equations for finding reflection coefficient or S_{11} values for normal and single tumor containing skin tissue accurately in the range from 58 to 61 GHZ and in the higher ranges of 70 to 75 GHz, as indicated from Figures 8 and 9.

Contribution of this research is in the provision of analytical/ statistical reflection channel impulse response for normal and tumor containing skin tissue.

Our proposed mathematical model can be further extended to be used not only in the forecasting of the dielectric properties and S_{11} values at frequencies where experimental results are not available but also in the design of communication receivers and antennas for biomedical purposes in skin cancer research.

VII. ACKNOWLEDGEMENTS

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