Calibrated Free-Space Microwave Measurements with an Ultrawideband Reflectometer-Antenna System

Min Zhao, *Student Member, IEEE*, Jacob D. Shea, *Student Member, IEEE*,
Susan C. Hagness, *Senior Member, IEEE,* Daniel W. van der Weide, *Member, IEEE*

***Abstract*—We present a 3 to 12 GHz compact mixer-based reflectometer (CMR) and horn antenna system, and demonstrate its use in detecting backscatter signals with a free space calibration procedure. We evaluate the frequency-domain performance of the CMR-antenna system for measuring the complex reflection coefficient of a dielectric slab and compare it with that of a commercial vector network analyzer (VNA)-antenna setup. Time-domain responses are also investigated, and show the effectiveness of this calibration method. This low-cost, compact system eliminates the need for traditional mechanical standards and a VNA, is effective in reducing reflection artifacts, and allows for flexibility in the placement of reference planes; thus it is well suited for array-based imaging applications.**

***Index Terms*—Antennas, biomedical imaging, calibration, microwave measurements, reflectometer, ultrawideband.**

I. Introduction

ULTRAWIDEBAND (UWB) microwave backscatter imaging systems have been widely developed for numerous detection applications, such as breast tumor detection [1],[2]. Current techniques typically employ UWB antennas in combination with a commercial vector network analyzer (VNA) to receive and measure the backscattered signals. However, the prohibitive cost and bulky size of VNAs make this approach unsuitable for multi-channel array-based system configurations. Moreover, the traditional calibration procedures used with these systems require mechanical contact and do not compensate for antenna dispersion, mechanical artifacts or reverberation.

A variety of free space measurement systems and calibration techniques have been reported for use in the microwave regime [3]–[7]. Most of the techniques rely on the use of a commercial VNA. The measurement systems in [3][4] are based on a two-port thru-reflect-line (TRL) calibration. A modified reduced-cost measurement system which follows this approach is reported in [5]. Reference [6] constructs a two-parameter model to approximate antenna-media coupling and uses shifted metal plates as calibration standards. Reference [7] discusses free space calibration procedures using two-term and three-term error models, as well as free space calibration standards and errors associated with the calibration methods.

This work was supported by the Department of Defense Breast Cancer Imaging Research Program under Grant W81XWH-04-1-0356, a University of Wisconsin Graduate Fellowship, and Tera-X LLC.

The authors are with the Department of Electrical and Computer Engineering at the University of Wisconsin, Madison, WI 53706 USA (emails: minz@cae.wisc.edu; shea@cae.wisc.edu; hagness@engr.wisc.edu; danvdw@engr.wisc.edu).

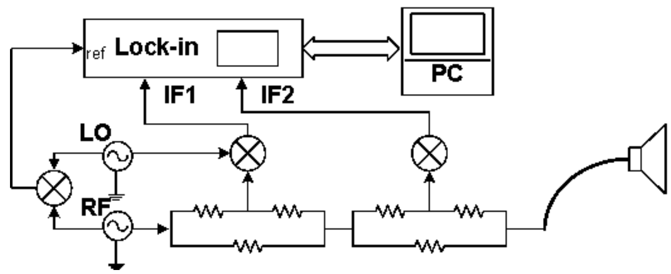


Fig. 1. System diagram: The compact mixer-based reflectometer (CMR) and a compact UWB horn antenna are connected through a semi-rigid cable.

In this letter, we present a calibrated free space measurement procedure for a monostatic system comprised of a compact mixer-based reflectometer (CMR) [8] and a UWB horn antenna. Our calibration procedure involves a pre-calibration using the empty room standard case, a time-gating process, and a three-term one-port error model. Multiple versions of the low-cost CMR circuit block, as shown in Fig.1, can be arranged in parallel for array-based systems. This contactless measurement system eliminates the need for connectorized mechanical standards at the reference planes, thus providing better measurement reliability and repeatability. The calibration method compensates for the UWB antenna dispersion, the reverberation from the antenna, and reflections between the antenna and the material under test (MUT). It also allows for flexibility in the choice of reference plane positions.

II. Theory

In our system, the output port of the CMR is connected to a compact UWB horn antenna through a semi-rigid cable, as shown in Fig. 1. We use the measurement and calibration procedure described below to compensate for the error sources and measurement artifacts inherent in the whole system.

First, we extract the broadband pre-calibrated measured reflection coefficient Γ_{raw} from the raw outputs *IF1* and *IF2* (shown in Fig. 1) of the CMR [8]. X is a pre-calibration coefficient determined by forcing the Γ_{raw} of the empty room case to be zero.

$$\Gamma_{raw} = X \cdot (IF1) - (IF2) \tag{1}$$

Second, we apply a time-gating step to obtain a smoothed reflection coefficient Γ_G as in (2). We desire to consider only the time-domain reflection signal contributions from the standards or MUT. Thus, a window function *H(t)* is selected which excludes any other reverberation or background noise and clutter that fall outside the window. This window is applied to the inverse discrete Fourier transformed time-domain data $F^{-1}(\Gamma_M)$. As a result, a time-gated response Γ_G is obtained by Fourier transforming the time-domain gated information back into the frequency domain:

$$\Gamma_G = F\left\{F^{-1}\left(\Gamma_{raw}\right)\cdot \mathrm{H}\left(t\right)\right\} \tag{2}$$

Finally, we apply a one-port error model [9] to extract the free space system error terms e_1, e_2, e_3, and to obtain the calibrated reflection coefficient Γ_C as in (3).

$$\Gamma_C = \frac{\Gamma_G - e_1}{e_2 + e_3 \cdot \left(\Gamma_G - e_1\right)} \tag{3}$$

In our free-space measurement system, e_1 represents the return loss present in the CMR circuit and the mismatch between the CMR and antenna; e_2 accounts for any UWB antenna dispersion, multipath effects, semi-rigid cable loss and free space path loss; e_3 takes into account the multiple reflections returning from the MUT. To find the error terms, we employ three known calibration standards: 'Empty room' (load), a flat copper sheet placed at the reference plane (reference short), and the same copper sheet shifted a distance Δd away from the reference plane (offset short), as shown in Fig. 2. The reference plane is placed in the far field region for our application. Finally, the three error terms are obtained from (4) and used to determine the unknown material reflection coefficient calibration. Γ_{ER}, Γ_{RS}, and Γ_{OS} are the time gated reflection coefficients of the three standards.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & -(\Gamma_{RS} - \Gamma_{ER}) & -1 \\ 0 & -e^{-j\beta 2\Delta d}\left(\Gamma_{OS} - \Gamma_{ER}\right) & -e^{-j\beta 2\Delta d} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \Gamma_{ER} \\ \Gamma_{RS} - \Gamma_{ER} \\ \Gamma_{OS} - \Gamma_{ER} \end{bmatrix} \tag{4}$$

III. Prototyping and Measurement

We fabricated the compact (2 cm × 2 cm) microstrip-line based attenuator circuits used in the CMR as described in [8], and connected a UWB horn antenna to its output port through a 12 in semi-rigid SMA cable. The antenna used was the Tera-X Model 530, a 4.2 cm × 2.6 cm modified horn antenna that is based in part on work in [1],[10]. The RF input source was swept from 1 to 12 GHz with a step size of 50 MHz, yielding 221 data points. The RF power was optimized at +8 dbm. As

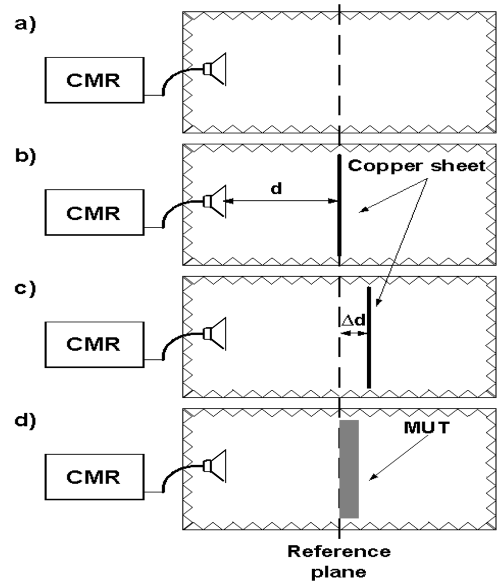


Fig. 2. The controlled experiment setups in our free-space calibration and measurement procedure.

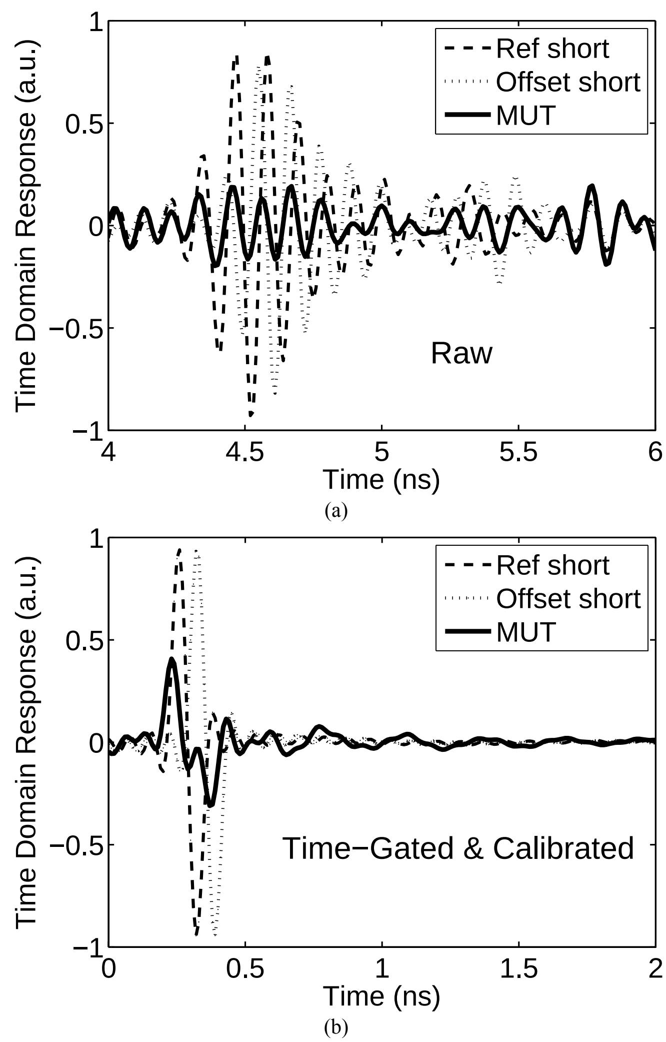
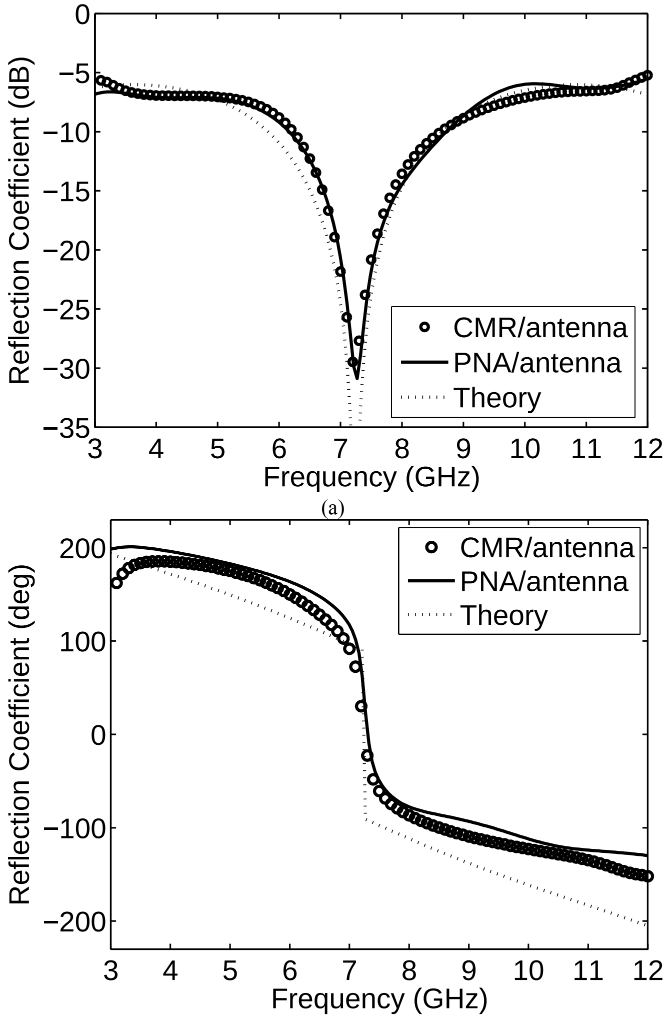


Fig. 3. (a) Raw time-domain responses from the standards and MUT. (b) Time-gated and calibrated time-domain responses from the standards and MUT, with the reference plane position as shown in Fig. 2.

shown in Fig. 2, the free-space calibration and measurement area was shielded with absorbing foam (ECCOSORB-AN) to



(b)

Fig. 4. Measured and calibrated complex reflection coefficients of a silicone rubber sheet (ε_r: 3.0, t: 0.471 in). The measurement results obtained from our CMR/antenna system are compared with those obtained using PNA/antenna setup as well as with the theoretical values.

provide an anechoic environment (24 in × 30 in × 30 in). We also used optical rails to achieve precisely controlled and repeatable standard placement. With respect to the trade-off between a reasonable SNR and far-field region requirement, we chose the reference plane to be 10 cm away from the antenna aperture. A 12 in × 12 in copper sheet was used as the reference short and the offset short standards; whereas a 12 in × 12 in flat silicone rubber sheet (ε_r: 3.0, thickness: 0.471 in, Durometer: 70 A) served as the MUT.

The calibrated time-domain responses in Fig. 3 show a vivid picture of the effectiveness of our free-space calibration. Fig. 3 plots the inverse discrete Fourier transformed time-domain return pulses from the standards as well as the MUT, both prior to calibration, i.e., $F^{-1}(\Gamma_M)$, and after time-gating and free-space calibration, i.e., $F^{-1}(\Gamma_A)$. A bandpass Gaussian window is used in the transformation. Without calibration, the original reference plane for the time-domain observation is at the output port of the CMR. The pulses complete a round trip, traveling through the semi-rigid cable and over the free-space path, then being reflected and returning. As in Fig. 3(a), they arrive approximately 4.3ns after passing the CMR reference plane. In Fig. 3(b), the calibrated return pulses are observed immediately after a time delay defined for the modulated Gaussian source pulse because the reference plane has been relocated by the free-space calibration procedure. It is apparent that the pulse broadening due to dispersion in the circuit and antenna is effectively compensated.

Figure 4 shows the calibrated complex reflection coefficients of a silicone rubber sheet measured using the CMR-antenna system. This result compares favorably with those obtained using an Agilent performance network analyzer (PNA) E8364A-antenna setup in the frequency range of 3 to 12 GHz. For our experiments, both instrument configurations employed the same free-space calibration procedure and controlled measurement setup. The result also compares well with the theoretical reflection coefficient. As expected, the response below 3 GHz does not merit consideration due to antenna gain limitations at lower frequencies.

IV. Conclusion

A 3 to 12 GHz reflectometer-antenna front end system with the associated calibration method shows promise for eliminating reflection artifacts and dispersion in free-space reflection coefficient measurements. This system is suitable for use in future compact, low cost array-based detection applications, including medical imaging.

References

[1] X. Li, S. K. Davis, S. C. Hagness, D. W. van der Weide, and B. D. Van Veen, "Microwave imaging via space-time beamforming: Experimental investigation of tumor detection in multilayer breast phantoms," *IEEE Trans. Microw. Theory Tech.,* vol. 52, no. 8, pp. 1856-1865, Aug. 2004.

[2] J. M. Sill and E. C. Fear, "Tissue sensing adaptive radar for breast cancer detection – experimental investigation of simple tumor models," *IEEE Trans. Microw. Theory Tech.,* vol. 53, no. 11, pp. 3312-3319, Nov. 2005.

[3] D. K. Ghodgaonkar, V. V. Varadan, and V. K. Varadan, "A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies," *IEEE Trans. Instrum. Meas.,* vol. 37, no. 3, pp. 789-793, Jun. 1989.

[4] D. K. Ghodgaonkar, V. V. Varadan, and V. K. Varadan, "Free-space measurement of complex permittivity and complex permeability of magnetic materials at microwave frequencies," *IEEE Trans. Instrum. Meas.,* vol. 39, no. 2, pp. 387-394, Apr. 1990.

[5] N. Gagnon, J. Shaker, L. Roy, A. Petosa and P. Berini, "Low-cost free-space measurement of dielectric constant at Ka band," *IEE Proc.-Microw. Antennas Propag.,* vol. 151, no. 3, pp. 271-276, Jun. 2004.

[6] M. Nakhkash, Y. Huang, W. Al-Nuaimy, and M. Fang, "An improved calibration technique for free-space measurement of complex permittivity," *IEEE Trans. Geo. Remote Sensing,* vol. 39, no. 2, pp. 453-455, Feb. 2001.

[7] F. C. Smith, B. Chambers, and J. C. Bennett, "Calibration techniques for free space reflection coefficient measurements," *IEE Proc. A-Science, Meas. and Tech.,* vol. 139, no. 5, pp. 247-253, Sep. 1992.

[8] M. K. Choi, M. Zhao, S. C. Hagness, and D. W. van der Weide, "Compact mixer-based 1-12GHz reflectometer," *IEEE Microw. Wireless Comp. Lett.,* vol. 15, no. 11, pp. 781-783, Nov. 2005.

[9] B. A. Brown. (2004) Solving the One-Port Calibration Equations. Tech. Rep. [Online]. Available: http://www.vnahelp.com/tip20.html

[10] X. Li, S. C. Hagness, M. K. Choi, and D. W. van der Weide, "Numerical and experimental investigation of an ultrawideband ridged pyramidal horn antenna with curved launching plane for pulse radiation," *IEEE Antennas Wireless Propag. Lett.,* vol. 2, pp. 259-262, 2003.