SAR COMPLIANCE TESTING OF CYBERTAN TECHNOLOGY MODEL WE701-I IEEE 802.11a/b/g WIRELESS LAN CARDBUS CARD INSERTED INTO DELL MODEL PP01L NOTEBOOK COMPUTER

FCC ID# N89-WE701I

Wireless LAN Cardbus Card Model WE701-I

Host Computer: Dell Model PP01L
S/N: TW-0791UH-12800-0CK-3735

February 14, 2004

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I. Introduction

We have used the measurement procedures outlined in FCC Supplement C (Edition 97-01) to OET Bulletin 65 [1] and an updated version of the same [2] for evaluating compliance of the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer. Three photographs of the Dell Model PP01L Host Computer with Cybertan Technology Wireless LAN Cardbus Card are given in Figs. 1a-c respectively. The Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) uses two identical antennas that operate over the frequency band 5.18 to 5.805 GHz in normal mode with peak-conducted powers that are given in Table 1.

For SAR measurements, two configurations of the wireless PC relative to the experimental phantom have been used. These are as follows:

a. **Configuration 1** is for the wireless PC placed on a user's lap. For this configuration, a planar phantom model with inside dimensions 12" × 16.5" (30.5 × 41.9 cm) and a base thickness of 2.0 ± 0.2 mm (recommended in [2]) was used for SAR measurements and the bottom side of the laptop computer shown in Fig. 1 was pressed against it (see Fig. 2). For this configuration, the SARs were extremely low close to the noise level of the measuring system (estimated to be on the order of 0.02 W/kg) for the lower frequency band frequencies of 5.18 and 5.26 GHz,

respectively. This is likely due to use of an excellent ground and fairly low radiated powers that are used for this cardbus card.

b. **Configuration 2** – Edge-on position. This configuration corresponds to a bystander close to the outer edge of the Cardbus Card. For this configuration, the PC is placed at 90º with the edge of the Cybertan Technology Wireless LAN Cardbus Card pressed against the bottom of the planar phantom. A photograph for this edge-on position for SAR testing is given in Fig. 3.

II. The SAR Measurement System

The University of Utah SAR Measurement System has been described in peer-reviewed literature [3]. A photograph of the SAR Measurement System is given in Fig. 4. This SAR Measurement System uses a computer-controlled 3-D stepper motor system (Arrick Robotics MD-2A). A triaxial Narda Model 8021 E-field probe is used to determine the internal electric fields. The positioning repeatability of the stepper motor system moving the E-field probe is within ± 0.1 mm. Outputs from the three channels of the E-field probe are dc voltages, the sum of which is proportional to the square of the internal electric fields $\left(|E_i|^2\right)$ from which the SAR can be obtained from the equation SAR = $s\left(|E_i|^2\right)/r$, where σ and ρ are the conductivity and mass density of the tissue-simulant materials, respectively [4]. The dc voltages for the three channels of the E-field probe are read by three HP 34401A multimeters and sent to the computer via an HPIB interface. The setup is carefully grounded and shielded to reduce the noise due to the electromagnetic interference (EMI). A cutout in a wooden table allows placement of a plastic holder (shown in Fig. 5) on which the laptop computer with the 802.11a wireless antennas (see Fig. 1) is supported. The plastic holder (see Fig. 5) can be moved up or down so that the base of the PC (for Configuration 1) is pressed against the base of the flat phantom for determination of SAR for Above-lap position (see Fig. 2). Similarly, for "Edge-On" SAR determination, Configuration 2, the laptop computer is mounted sideways (at 90°) on the plastic holder and moved up so that the edge of the Cybertan Technology Wireless LAN Cardbus Card is pressed against the bottom of the flat phantom (see Fig. 3).

The Flat Phantom

As recommended in Supplement C Edition 01-01 to OET Bulletin 65 [2], a planar phantom model with inside dimensions 12" × 16.5" (30.5 × 41.9 cm) and base thickness 2.0 ± 0.2 mm was used for SAR measurements (see Figs. 2, 3).

III. Calibration of the E-Field Probe

The IEEE Standard P1528 [5] suggests a recommended procedure for probe calibration (see Section 4.4.1 of [5]) for frequencies above 800 MHz where waveguide size is manageable. Calibration using an appropriate rectangular waveguide is recommended. As in some previously reported SAR measurements at 6 GHz [4], we have calibrated the Narda Model 8021 Miniature Broadband Electric Field Probe of tip diameter 4 mm (internal dipole dimensions on the order of 2.5 mm) using a rectangular waveguide WR 159 (of internal dimensions 1.59 × 0.795 inches) that was filled with the tissue-simulant fluid of composition given in Section V (see Figs. 2, 3). The triaxial (3 dipole) E-field probe shown in Fig. 7 was originally developed by Howard Bassen and colleagues of FDA and has been manufactured under license by Narda Microwave Corporation, Hauppage, New York. The probe is described in detail in references 6 and 7. It uses three orthogonal pick up dipoles each of length about 2.5 mm offset from the tip by 3 mm, each with its own leadless zero voltage Schottky barrier diode operating in the square law region. The sum of the three diode outputs read by three microvoltmeters [3] gives an output proportional to E^2. By rotating the probe around its axis, the isotropy of the probe was measured to be less than ± 0.23 dB and the deviation of the probe from the square law behavior was less than ± 3%.

As suggested in the IEEE Standard P1528, the waveguide (WR 159) filled with the tissue-simulant fluid was maintained vertically. From microwave field theory [see e.g. ref. 8], the transverse field distribution in the liquid corresponds to the fundamental mode (TE_{10}) with an exponential decay in the vertical direction (z-axis). The liquid level was 15 cm deep which is deep enough to guarantee that reflections from the top liquid surface do not affect the calibration. By comparing the square of the decaying electric fields expected in the tissue from the analytical expressions for the TE_{10} mode of the

rectangular waveguide, we obtained a calibration factor of 2.98 (mW/kg)/μV with a variability of less than ± 2% for measurement frequencies of 5.25 and 5.8 GHz, respectively. This is no doubt due to a fairly limited frequency band of only 0.55 GHz out of a recommended bandwidth of 2.2 GHz for the TE_{10} mode for the WR159 waveguide (recommended band of 4.9-7.1 GHz -- see e.g. ref. 8) and the fact that the bandwidth of 550 MHz for the entire set of measurements is on the order of ± 5% of the midband frequencies.

The date for the calibration of the E-field probe closest to the SAR tests given here was February 13, 2004.

To verify that the probe calibration conducted for the 802.11a band with CW signals is also valid for modulated signals used for the Cardbus Adapter, two procedures have been used. These are described in Appendix A.

IV. SAR System Verification

It is very difficult to develop half wave dipole antennas for use in the 5.2 to 5.8 GHz band both because of fairly small dimensions and the resulting dimensional tolerances, and relatively narrow bandwidths of the required baluns – balanced-to-unbalanced transformers. On the other hand, waveguides are broadband with simultaneous bandwidths larger than 1-2 GHz and fairly easy to use for frequencies in excess of 3 GHz. As shown in Fig. 8, we have, therefore, developed a system verification system by using an open-ended, air-filled waveguide as an irradiation system placed at a distance of 8 mm below the base of the planar phantom (10 mm from the lossy fluid in the phantom). For this application, we have set up a WR 187 rectangular waveguide of internal dimensions 1.872" × 0.872" that is fed with microwave power from a Hewlett Packard Model 83620A Synthesized Sweeper (10 MHz-20 GHz). The operating (TE_{10} mode) band of this waveguide is from 3.95 to 5.85 GHz. The microwave circuit arrangement used for system verification is sketched in Fig. 9. When placed at a distance of 8 mm from the base of the planar phantom, the reflection coefficient is about 10-20%. As seen in Fig. 8, even this relatively small amount of reflection has been reduced to less than 0.5% by using a movable slide-screw waveguide tuner (Narda Model 22CI). The measured SAR

distribution for peak 1-g SAR region using this system at 5.25 and 5.8 GHz for the day of the SAR measurements February 13, 2004, are given in Appendix B. Also given in Appendix B are the waveguide SAR plots for this date of SAR measurements. The peak 1-g SARs measured for 100 mW of radiated power for 5.25 and 5.8 GHz were 3.66 and 4.01 W/kg, respectively. The measured 1-g SARs are in excellent agreement with the FDTD-calculated 1-g SAR for this waveguide of 3.580 and 3.946 W/kg at 5.25 and 5.8 GHz, respectively. Also as expected, the measured SAR plots in Appendix B are quite symmetric at the irradiation frequency.

For FDTD-calculations of the SAR distributions for the WR187 rectangular waveguide irradiation system, we have used the dielectric properties for the phantom given in Table 2 that have been taken from [2]. Using a resolution of 0.5 mm for the FDTD cells, the calculated variations of the SAR distributions are given in Figs. 10a, b as a function of height above the bottom surface of the phantom. From Figs. 10a, b, it is obvious that the penetration of electromagnetic fields in the 5.2-5.8 GHz range is extremely shallow. The calculated depths of penetration corresponding to $1/e^2$-reduction of SAR (13.5% of the SAR at the surface) are only 6.85 and 5.95 mm at 5.25 and 5.8 GHz, respectively. Both of these depths of penetration for this near-field exposure system are very similar to those obtained for plane wave irradiation at these frequencies (7.15 mm for 5.25 GHz and 6.25 mm for 5.8 GHz).

Also shown in Figs. 10a, b are the SAR variations measured for this waveguide exposure system at depths of 4, 6, 8, 10, 12, and 14 mm in the tissue-simulant fluid. We tried second-, third-, fourth-, and fifth-order polynomial least-square fits to extrapolate the measured SARs to depths of 1, 3, 5, 7, and 9 mm. As seen in Figs. 10a, b, the fourth-order polynomial provides an excellent agreement with the FDTD-calculated in-depth variation of SAR both at 5.25 and 5.8 GHz. Also as aforementioned, the peak 1-g SARs thus obtained for 100 mW of radiated power for 5.25 and 5.80 GHz of 3.66 and 4.03 W/kg are extremely close to the FDTD-calculated 1-g SARs for this waveguide of 3.580 and 3.946 W/kg at the two frequencies, respectively.

V. Tissue Simulant Fluid for the Frequency Band 5.2 to 5.8 GHz

In OET 65 Supplement C [2], the dielectric parameters suggested for body phantom are given only for 3000 and 5800 MHz. These are listed in Table 2 here. Using linear interpolation, we can obtain the dielectric parameters to use for the frequency band between 5.25 to 5.8 GHz. The desired dielectric properties thus obtained are also given in Table 2. From Table 2, it can be noticed that the desired dielectric constant ε_r varies from 48.2 to 49.0 which is a variation of less than ± 1% from the average value of 48.6 for this band. Also the conductivity σ varies linearly with frequency from 5.36 to 6.00 S/m.

No tissue-simulant fluids have been suggested in any of the existing standards or draft standards [2, 5, 9, 10]. Because of this limitation, some of the standards are only written for frequencies up to 3 GHz [e.g. refs. 5, 9]. We have developed a fluid composition for which the measured dielectric properties for the 802.11a frequencies of 5.25 and 5.80 GHz are as follows:

For 5.25 GHz,

$$\varepsilon_r = 49.6 \pm 0.6$$

$$\sigma = 5.35 \pm 0.09 \text{ S/m}$$

For 5.8 GHz,

$$\varepsilon_r = 49.3 \pm 0.6$$

$$\sigma = 6.01 \pm 0.1 \text{ S/m}$$

The measurements of the dielectric properties $(\varepsilon', \varepsilon'')$ for this fluid composition were conducted using Hewlett Packard Model 85070B Dielectric Probe and the latest software 85070d provided by Agilent Technologies. The measured data is based on 11 repeated measurements of which five representative screen dumps are given in Appendix C, Figs. C.1-C.5, respectively. For each of the cases, the conductivity s for the fluid may be obtained by multiplying ε'' by $\omega\varepsilon_o$ where $\omega = 2\pi f$ and ε_o is the permittivity of free space, 8.854 $\times 10^{-12}$ F/m. The measured values of ε_r and s given above are extremely close to the suggested values given in Table 2: $\varepsilon_r = 48.9$, $\sigma = 5.36$ S/m for 5.25 GHz and $\varepsilon_r = 48.2$ and $\sigma = 6.00$ S/m for 5.80 GHz.

VI. The Measured SAR Distributions

The RF power outputs measured for the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I for the normal mode are given in Table 1. For SAR measurements, we selected frequencies of 5.18, 5.26 and 5.805 GHz. The various frequencies were selected both for their highest power outputs as well as to cover the frequency bands planned for this PC. As recommended in Supplement C, Edition 01-01 [2], the stability of the conducted power was determined by repeated SAR measurements at the same location for each of the selected channels. The variability of the SAR thus determined for three repeated measurements over a 60-minute time period was within ± 0.1 dB (± 2.5%).

The highest SAR region for each of the measurement frequencies was identified in the first instance by using a coarser sampling with a step size of 8.0 mm over three overlapping areas for a total scan area of 11.2 × 19.2 cm. The data thus obtained was resolved into a 4 × 4 times larger grid i.e. a grid involving 56 × 96 points by linear interpolation using a 2 mm step size. After thus identifying the region of the highest SAR, the SAR distribution was then measured with a resolution of 2 mm in order to obtain the peak 1 cm^3 or 1-g SAR. The SAR measurements were performed at 4, 6, 8, 10, 12 mm height from the bottom surface of the body-simulant fluid. The SARs thus measured were extrapolated using a fourth-order least-square fit to the measured data to obtain the SAR variation correctly for the 802.11a frequencies of 5.2 to 5.8 GHz [11, attached as Appendix D]. This allowed us to obtain SAR values at 1, 3, 5, 7 and 9 mm height that were used to obtain 1-g SARs. The uncertainty analysis of the University of Utah SAR measurement system is given in Appendix E. The combined standard uncertainty is ± 8.3%.

Because of the fairly low radiated powers used for the Cybertan Technology Wireless LAN Cardbus Card (see Table 1), the measured SARs for this PC were fairly low, in fact too low to measure, and within the limit of the SAR measurement system (≤ 0.02 W/kg), for configuration 1-Laptop position for frequencies of 5.18 and 5.26 GHz, respectively (see Table 3). As determined by the coarse scans, the highest SAR region was invariably found for the 11.2 × 19.2 cm area immediately below the Cardbus Card for the "Above-lap" Configuration 1 for an irradiation frequency of 5.805 GHz

and above the projected area of the antenna for the "Edge-on" Configuration 2 for all of the test frequencies. The coarse scans for these highest SAR regions are given in Appendix F, Figs. F.1 to F.4. In these figures, the two axes are marked in units of step size of 8 mm. Also shown in these figures are the respective antenna outlines overlaid on the SAR contours. It is interesting to note that the highest SAR regions are immediately above the two antennas used for this Cardbus Card. Also given in Appendix F as Tables F.1 to F.4 are the SAR distributions for the highest SAR region of volume 10 × 10 × 10 mm for which the coarse scans are given in Figs. F.1 to F.4, respectively. The SARs are given for xy planes at heights Z of 1, 3, 5, 7, and 9 mm from the bottom of the flat phantom. The individual SAR values for this grid of 5 × 5 × 5 or 125 points are averaged to obtain peak 1-g SAR values (for a volume of 1 cm^3). The temperature variation of the tissue-simulant fluid measured with a Bailey Instruments Model BAT 8 Temperature Probe for measurements at the various frequencies was 22.4 ± 0.2°C.

The z-axis scan plots taken at the highest SAR locations for each set of tests are given in Appendix G. As discussed in Section IV, the SARs drop off fairly rapidly with depth in the phantom.

The SAR measurement results for the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer are summarized in Table 3. All of the measured 1-g SARs are less than the FCC 96-326 guideline of 1.6 W/kg.

VII. Comparison of the Data with FCC 96-326 Guidelines

According to the FCC 96-326 Guideline, the peak SAR for any 1-g of tissue should not exceed 1.6 W/kg. For the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer, the measured peak 1-g SARs vary from 0 to 0.125 W/kg which are smaller than 1.6 W/kg.

REFERENCES

1. K. Chan, R. F. Cleveland, Jr., and D. L. Means, "Evaluating Compliance With FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields," Supplement C (Edition 97-01) to OET Bulletin 65, December, 1997. Available from Office of Engineering and Technology, Federal Communications Commission, Washington D.C., 20554.

2. Federal Communications Commission "Supplement C Edition 01-01 to OET Bulletin 65 Edition 97-01" June 2001.

3. Q. Yu, O. P. Gandhi, M. Aronsson, and D. Wu, "An Automated SAR Measurement System for Compliance Testing of Personal Wireless Devices," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 41(3), pp. 234-245, August 1999.

4. O. P. Gandhi and J-Y. Chen, "Electromagnetic Absorption in the Human Head from Experimental 6-GHz Handheld Transceivers," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 39(4), pp. 547-558, 1995.

5. IEEE Standard P1528, "Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body Due to Wireless Communication Devices: Experimental Techniques," 2003.

6. H. Bassen. M. Swicord, and J. Abita, "A Miniature Broadband Electric Field Probe," Ann. New York Academy of Sciences, Vol. 247, pp. 481-493, 1974.

7. H. Bassen and T. Babij, "Experimental Techniques and Instrumentation," Chapter 7 in *Biological Effects and Medical Applications of Electromagnetic Energy*, O. P. Gandhi, Editor, Prentice Hall Inc., Englewood Cliffs, NJ, 1990.

8. O. P. Gandhi, *Microwave Engineering and Applications*, Pergamon Press, New York, 1981.

9. European Standard EN50361, "Basic Standard for the Measurement of Specific Absorption Rate Related to Human Exposure to Electromagnetic Fields from Mobile Phones (300 MHz-3 GHz)," CENELEC, Central Secretariat: rue de Stassart 35, B-1050, Brussels.

10. Draft IEC PT62209 Part 2, "Procedure to Measure the Specific Absorption Rate (SAR) for Two-Way Radios, Palmtop Terminals, Laptop Terminals, Desktop Terminals, and Body-Mounted Devices Including Accessories and Multiple Transmitters (30 MHz to 6 GHz)," Draft version 0.6.

11. Q. Li, O. P. Gandhi, and G. Kang, "An Open-Ended Waveguide System for SAR System Validation and/or Probe Calibration for Frequencies above 3 GHz," submitted for publication to *IEEE Transactions on Microwave Theory and Techniques*, June 2003 (attached here as Appendix D).

12. G. Kang and O. P. Gandhi, "Effect of Dielectric Properties on the Peak 1- and 10-g SAR for 802.11 a/b/g Frequencies 2.45 and 5.15 to 5.85 GHz," accepted for publication in *IEEE Transactions on Electromagnetic Compatibility.*

Table 1. Peak conducted RF power outputs measured at various frequencies for the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer for normal mode.

Channel	Frequency MHz	Intersil Setting	Peak Conducted RF Power (dBm)
Normal Mode			
1	5180	80	12.32
4	5240	80	12.08
5	5260	80	12.13
8	5320	80	12.07
9	5745	100	12.09
12	5805	105	12.11

Table 2. Dielectric parameters for body phantom for the frequency band 5.2 to 5.8 GHz [2].

Frequency (GHz)	ε_r	σ (S/m)	Reference
3.0	52.0	2.73	Ref. 2
5.8	48.2	6.00	Ref. 2
5.25	48.9	5.36	Interpolated
5.3	48.9	5.42	Interpolated
5.4	48.7	5.53	Interpolated
5.6	48.5	5.77	Interpolated
5.7	48.3	5.88	Interpolated

Table 3. The SAR measurement results for the normal mode of the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer.

Liquid temperature = 22.4 ± 0.2°C
Measurement date: February 13, 2004

Config-uration	Separation from Phantom (cm)	Mode	Frequency GHz	Conducted RF Output Power (dBm)		1-g SAR W/kg	See App. F Table	See App. F Figure
				Before	After			
1	0	Normal	5.18	12.32	12.36	< 0.02*	-	-
	0	Normal	5.26	12.13	12.08	< 0.02*	-	-
	0	Normal	5.805	12.11	12.15	0.102	F.1	F.1
2	0	Normal	5.18	12.32	12.30	0.076	F.2	F.2
	0	Normal	5.26	12.13	12.15	0.078	F.3	F.3
	0	Normal	5.805	12.11	12.13	0.125	F.4	F.4

* too low to measure; within the noise level of the SAR measurement system.

a. Top cover with screen open.

Fig. 1. Photograph of the Dell Model PP01L Host Computer with Cybertan Technology Wireless LAN Cardbus Card Model WE701-I inserted in it.

b. View from the bottom side of the laptop computer.

Fig. 1. Photograph of the Dell Model PP01L Host Computer with Cybertan Technology Wireless LAN Cardbus Card Model WE701-I inserted in it.

c. Side view showing the Cardbus Card edge.

Fig. 1. Photograph of the Dell Model PP01L Host Computer with Cybertan Technology Wireless LAN Cardbus Card Model WE701-I inserted in it.

Fig. 2. Photograph of the bottom of the Dell Model PP01L Host Computer with Cybertan Technology Wireless LAN Cardbus Card Model WE701-I pressed against the bottom of the planar phantom. This **Configuration 1 – Laptop position for SAR testing.**

Fig. 3. Photograph of the Dell Model PP01L Host Computer at 90º with the edge of the Cybertan Technology Wireless LAN Cardbus Card Model WE701-I pressed against the bottom of the planar phantom. This is **Configuration 2** for SAR testing and represents the case of a bystander at a distance of 0 cm from the edge of the Cardbus Card.

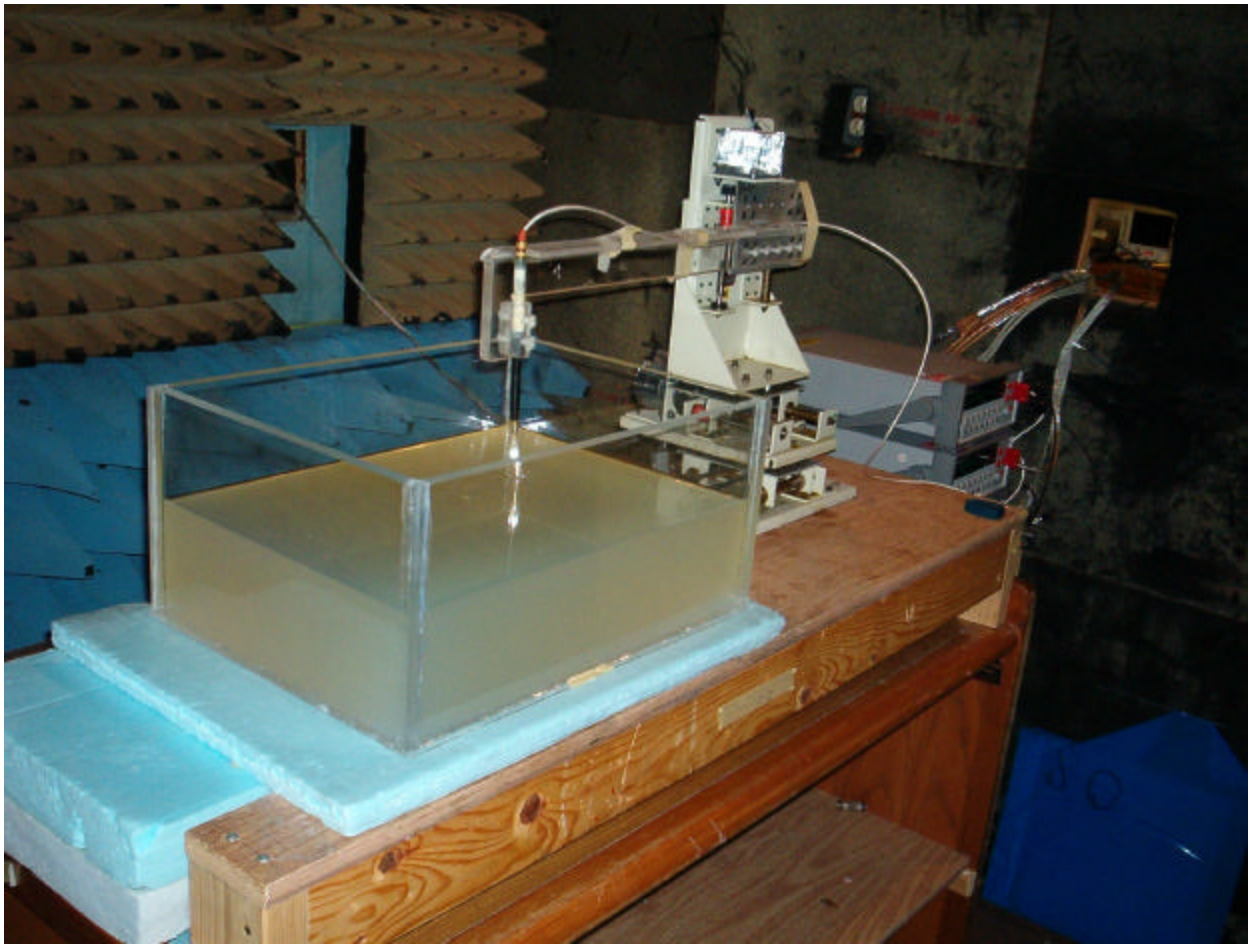


Fig. 4. Photograph of the three-dimensional stepper-motor-controlled SAR measurement system using a planar phantom.

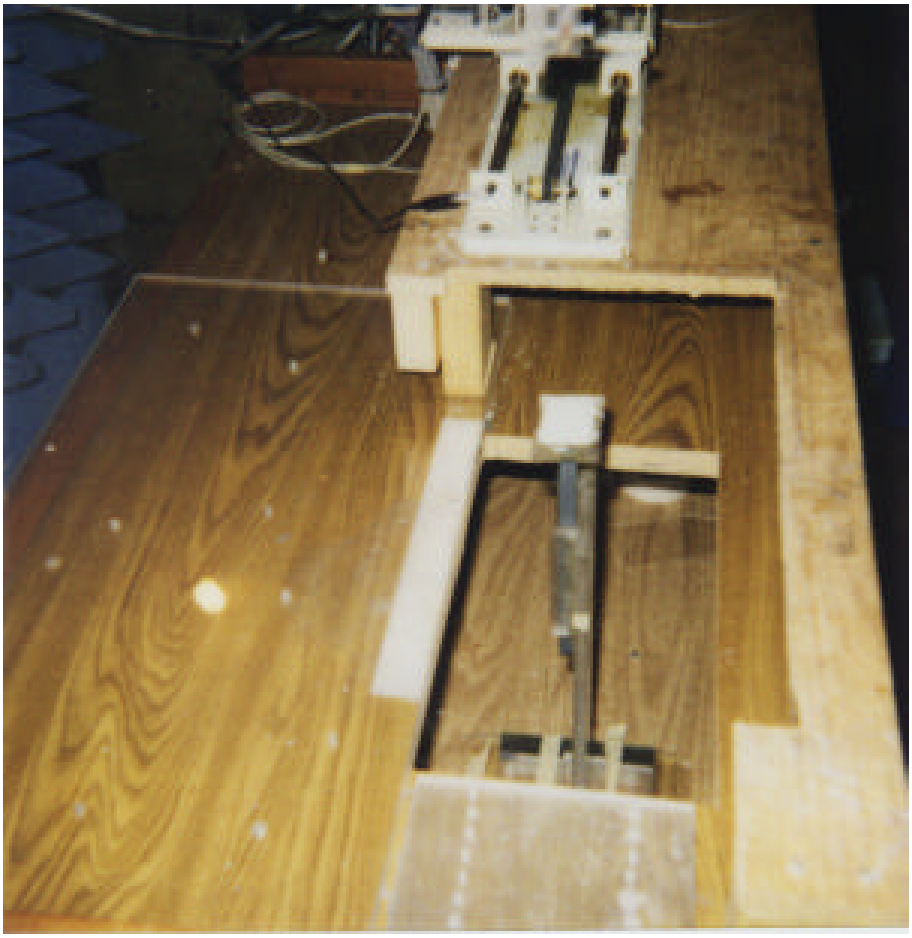


Fig. 5. The plastic holder used to support the portable PC for SAR measurements.

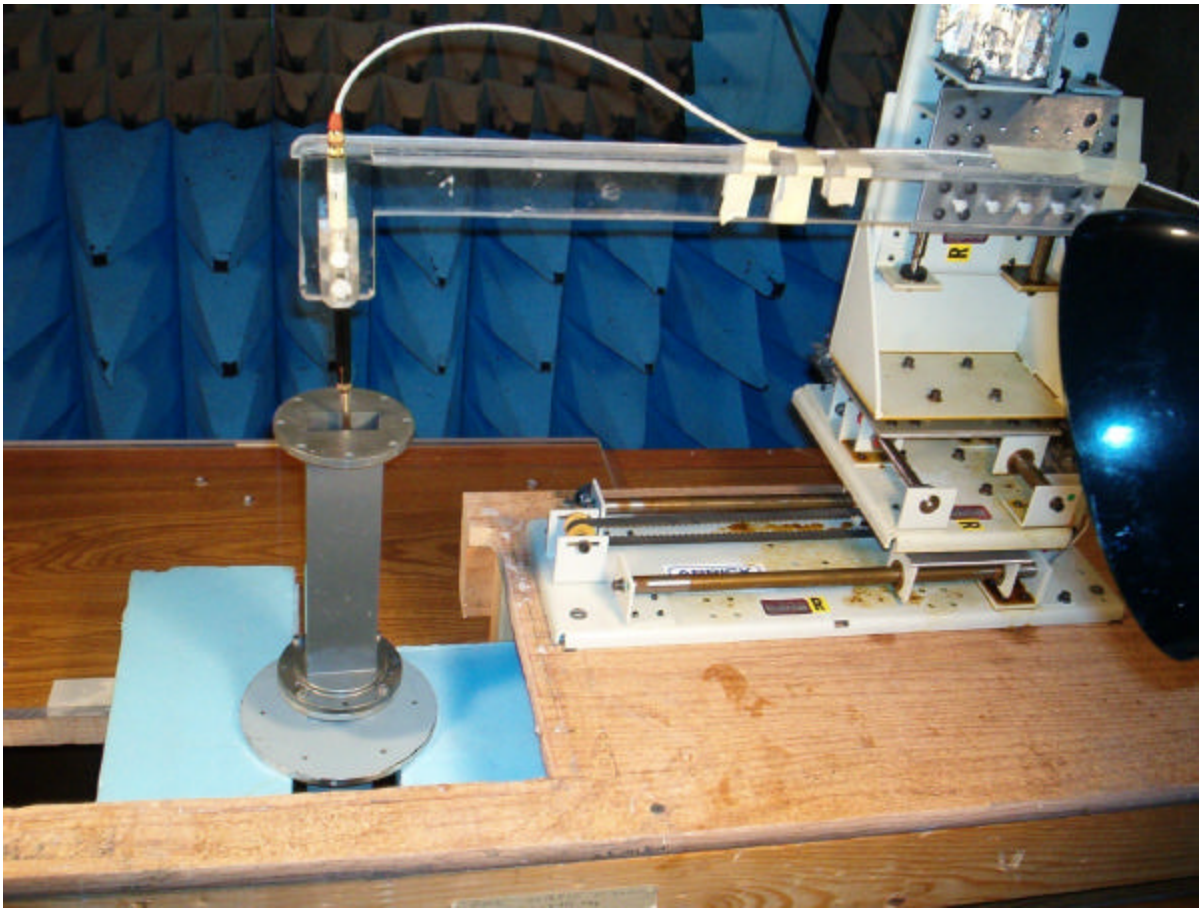


Fig. 6a. A photograph of the waveguide setup used for calibration of the Narda Model 8021 E-field probe in the frequency band 5.2-5.8 GHz.

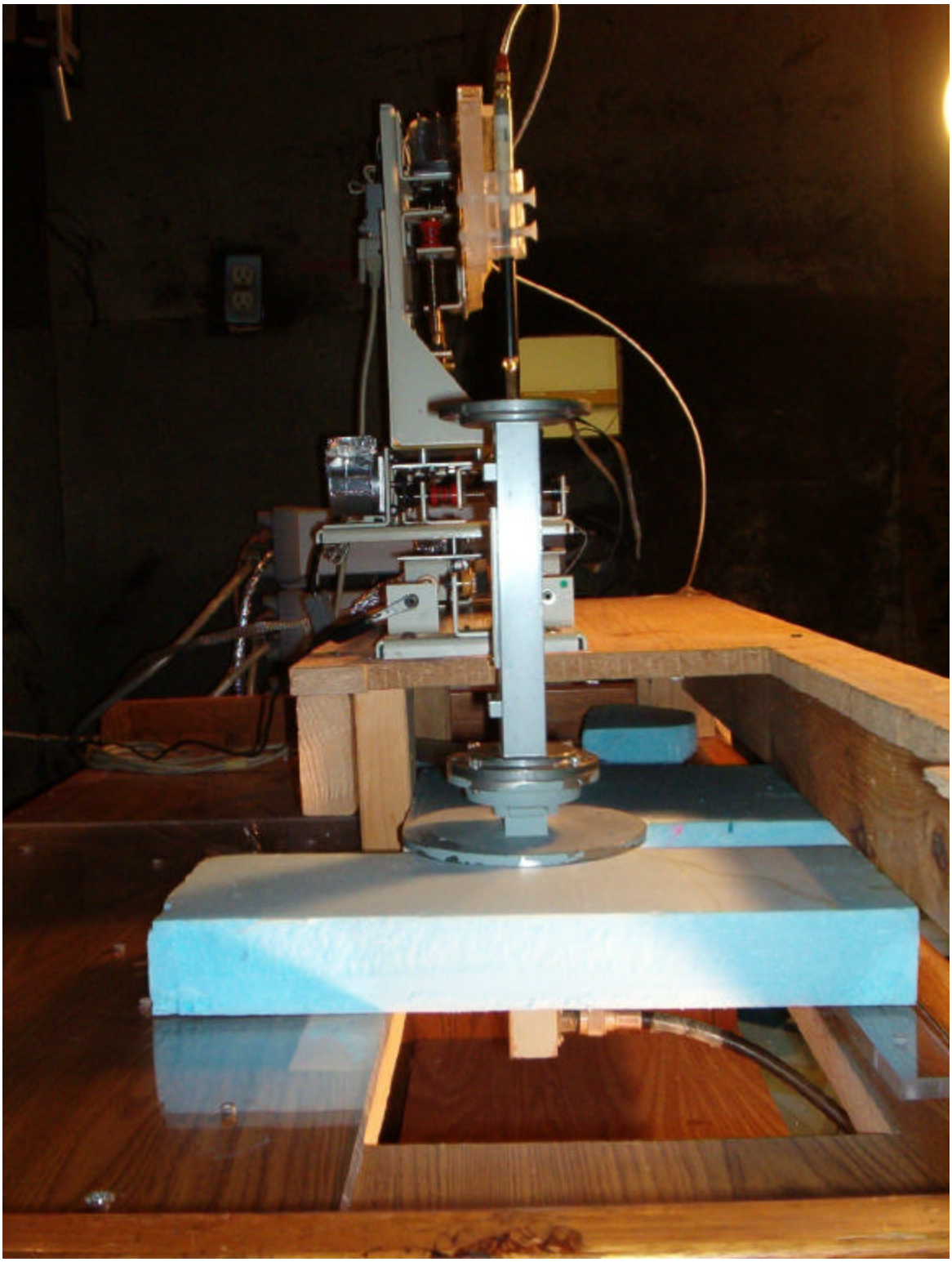


Fig. 6b. Photograph of the waveguide setup showing also the coax to waveguide coupler at the bottom used to feed power to the vertical waveguide containing the tissue-simulant fluid.

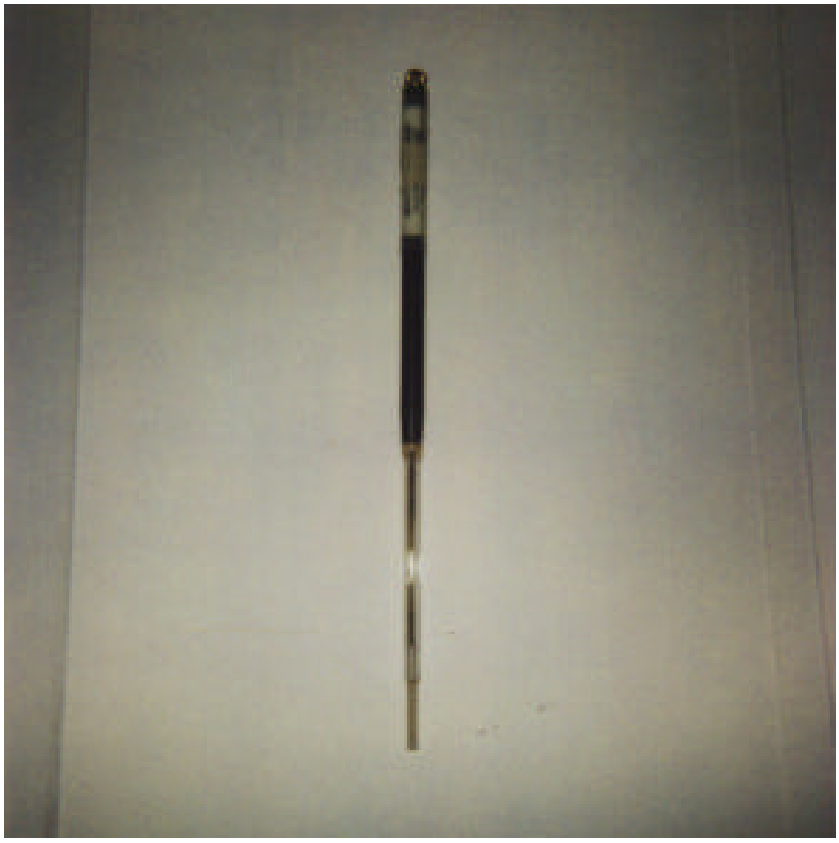


Fig. 7. Photograph of the Narda Model 8021 Broadband Electric Field Probe used for SAR measurements.

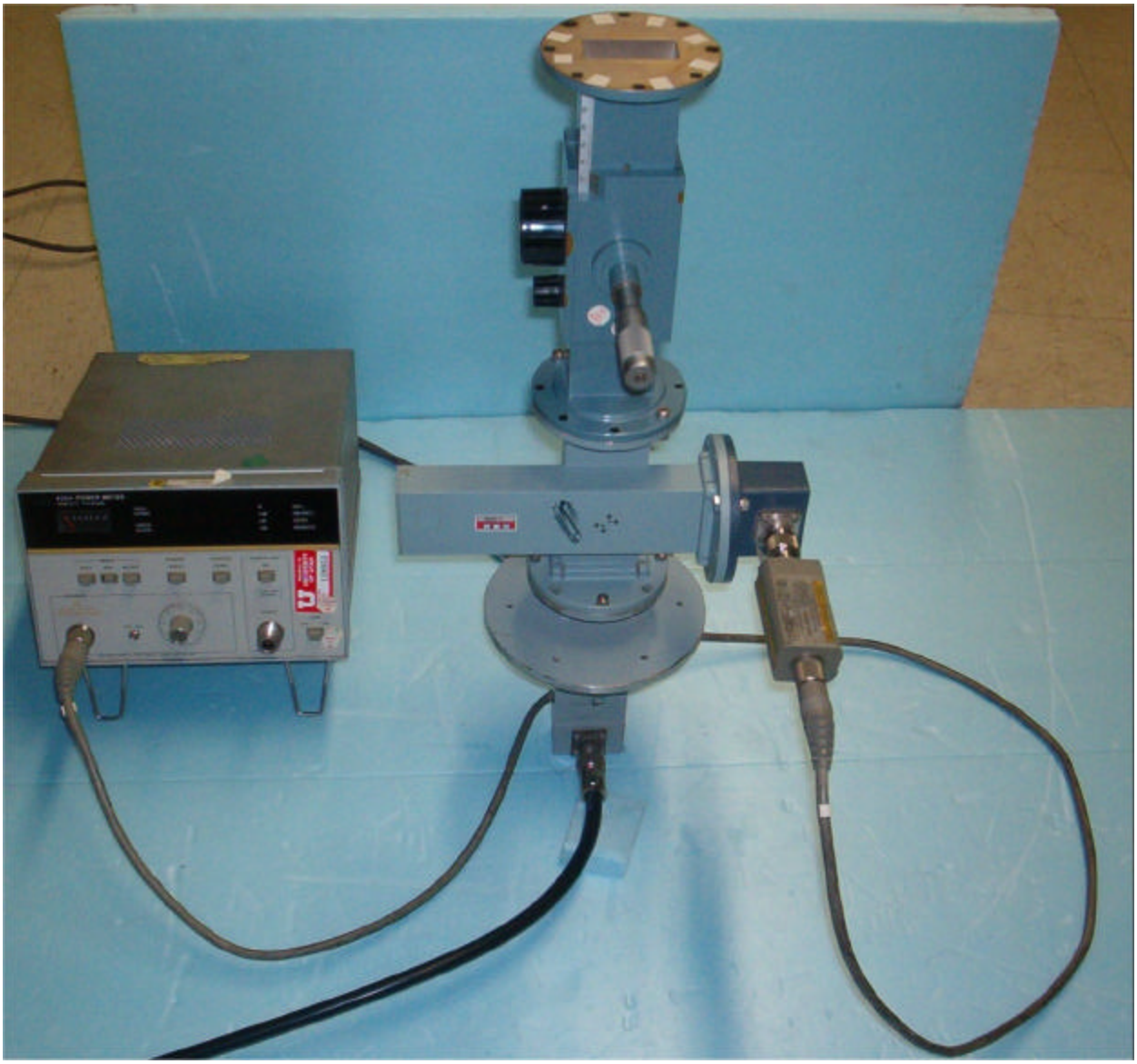
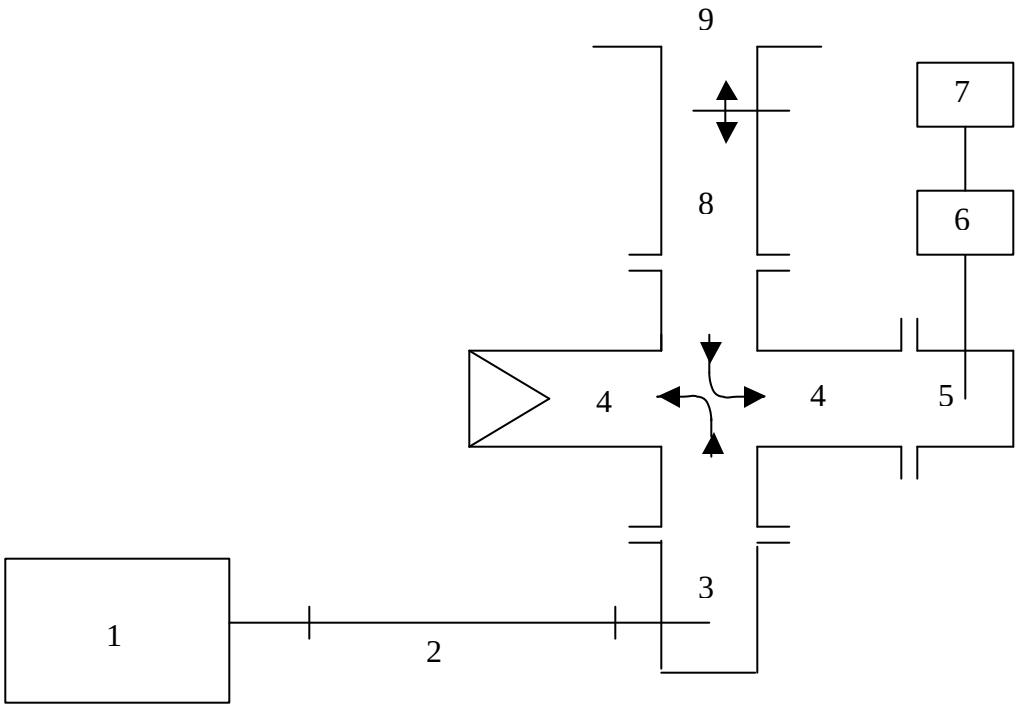
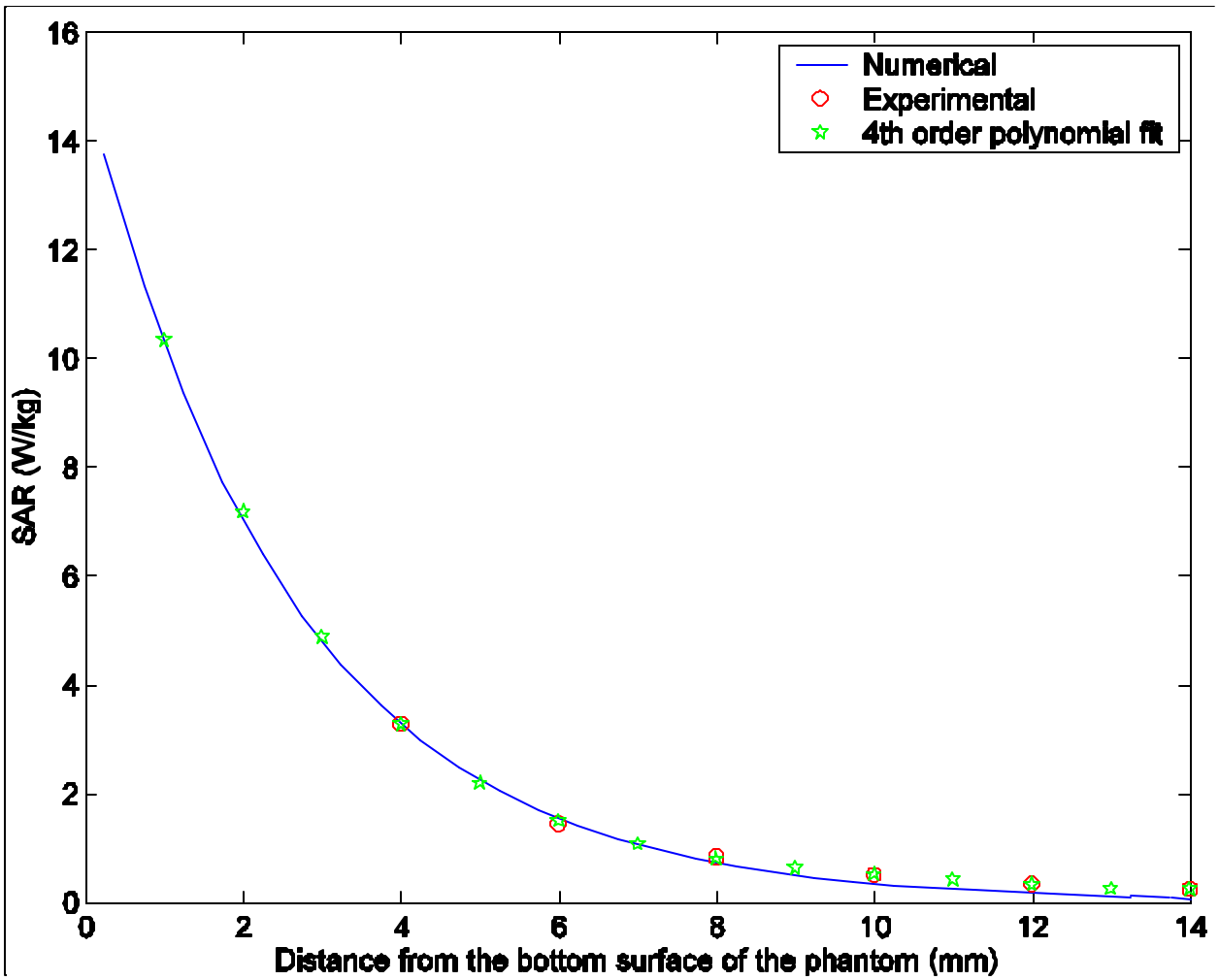


Fig. 8. Photograph of the rectangular waveguide radiator used for system verification for the 802.11a band. Also seen is the Narda Model 22CI movable slide screw tuner used to match the input power at 5.25 or 5.8 GHz to the planar phantom.



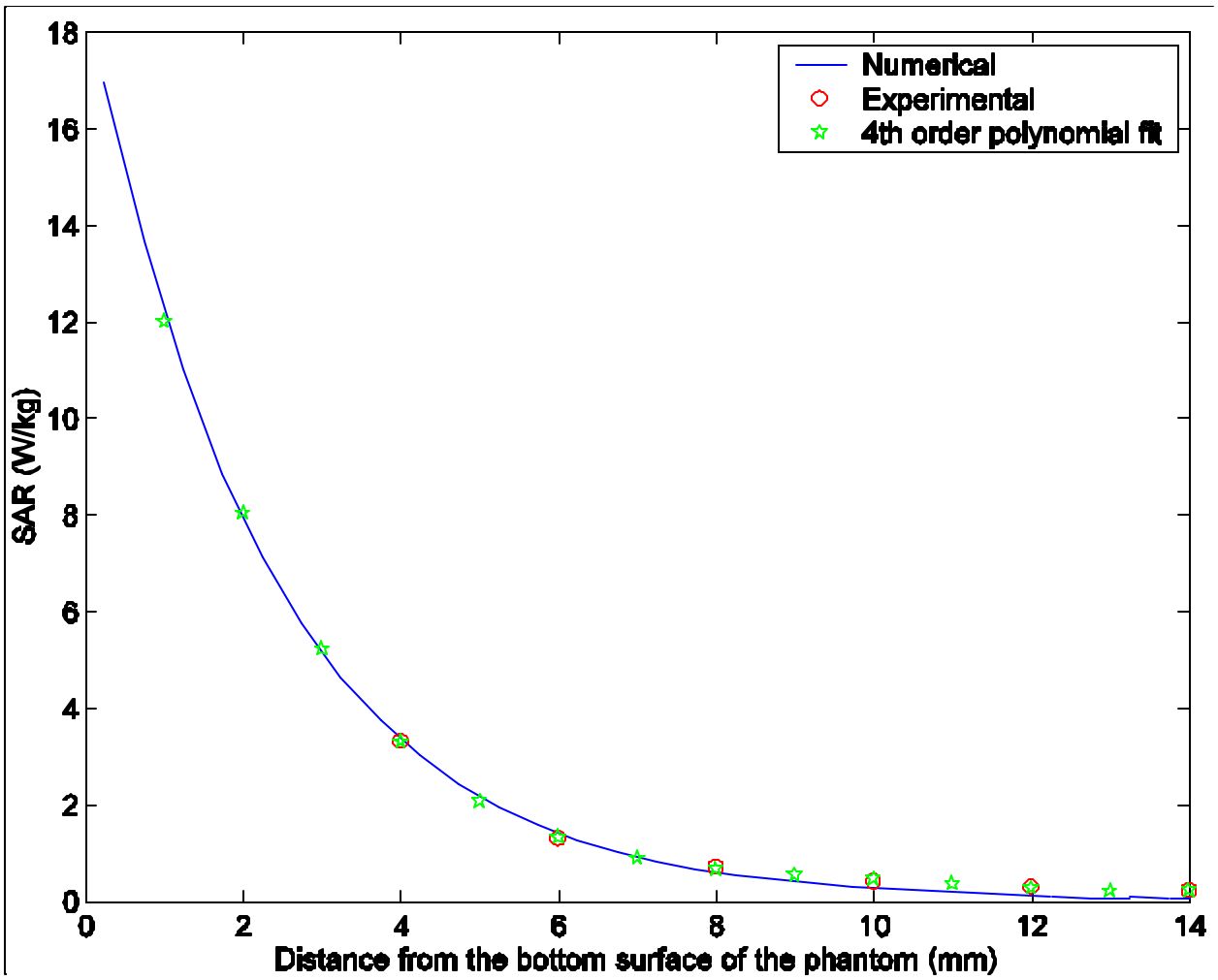
1. Hewlett Packard (HP) Model 83620A Synthesized Sweeper (10 MHz-20 GHz).
2. Coaxial line.
3. Coaxial to waveguide adapter.
4. 20 dB crossguide coupler (may be reversed to measure incident power).
5. HP Model G281A coaxial to waveguide adapter
6. HP Model 8482A power sensor.
7. HP Model 436A power meter.
8. Narda Microline® Slide Screw Tuner Model 22CI.
9. Radiating open end of the waveguide.

Fig. 9. The microwave circuit arrangement used for SAR system verification for the 802.11a band.



a. 5.25 GHz.

Fig. 10. Experimentally measured, extrapolated and FDTD-calculated variation of the SAR with depth in the body-simulant planar phantom. Radiated power = 100 mW.



b. 5.80 GHz.

Fig. 10. Experimentally measured, extrapolated and FDTD-calculated variation of the SAR with depth in the body-simulant planar phantom. Radiated power = 100 mW.

APPENDIX A

Procedures to Demonstrate that E-Field Probe Calibration for CW Signals is Also Valid for Modulated Signals

Procedure 1

For the microvoltmeters in our SAR system (HP34401 multimeters), we use an AC signal filter with a passband of 20 Hz to 300 kHz (1 reading/second). This allows faithful readings of the rectified values of voltage outputs from the three pickup antennas (proportional to E^2) of the E-field probe used for SAR measurements. For a variety of modulated signals used for the 802.11a band, the multimeter passband of 20 Hz to 300 kHz is more than sufficient to read all of the frequency components. We have tested the validity of using this AC signal filter by applying signals from a Hewlett Packard Model 83620A Synthesized Sweeper operating at 5.25 and 5.8 GHz in the CW mode as well as the pulse mode with pulse repetition rates for the latter variable from 50 to 500 Hz and pulse duration variable from 0.5 to 1 msec. For a fixed location of the E-field probe, the SAR readings were proportional to the time-averaged radiated power (from 2.5 to 100 mW) from the WR187 rectangular waveguide at 5.25 and 5.8 GHz, respectively. Thus the probe calibration factors are no different for CW signals or for pulsed signals.

Procedure 2

As explained above, the passband of our SAR measurement system extends from 20 Hz to 300 kHz. This passband is more than sufficient to read all of the frequency components associated with OFDM or any of the other modulations that may be used for the 802.11a band.

Additional experiments have, however, been done to compare the SAR measured at one of the points in the planar phantom for OFDM modulated signals from the 802.11a Mini PCI and comparing the same with the CW signal of similar time-averaged power levels obtained from the Hewlett-Packard (HP) Model 83620A Synthesized Sweeper (10 MHz-20 GHz). For each of the two RF sources, the power output was measured using a microwave circuit arrangement similar to that of Fig. 9 of the SAR

Report. As shown in this figure, the irradiation system uses a WR187 rectangular waveguide (see Fig. 8 of the SAR Report) which is placed at a distance of 8 mm below the base of the planar phantom (10 mm from the lossy fluid in the phantom) used for SAR measurements.

Shown in Figs. A.1 and A.4 is a comparison of the SARs measured for a given location in the planar phantom for CW and 802.11a band modulated signals for the base and turbo modes, for several frequencies of the 802.11a band, respectively. An excellent agreement in the SAR reading is observed whether CW or modulated signals are used. This is due to the broad bandwidth (20 Hz to 300 kHz) of the system used for measuring rectified signals from the E-field probe.

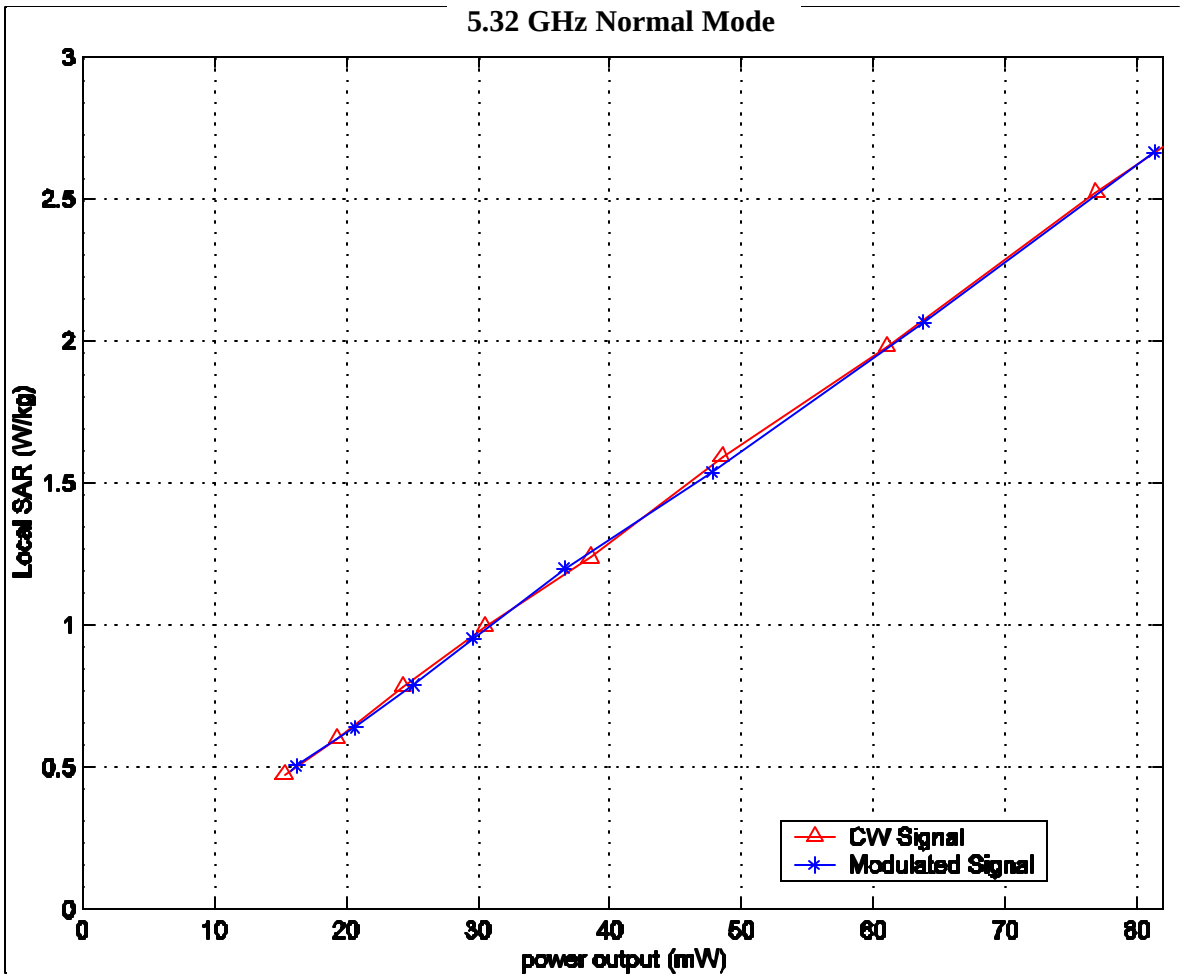


Fig. A.1. Comparison of the SAR for CW or OFDM modulated signals for the base mode at 5.32 GHz.

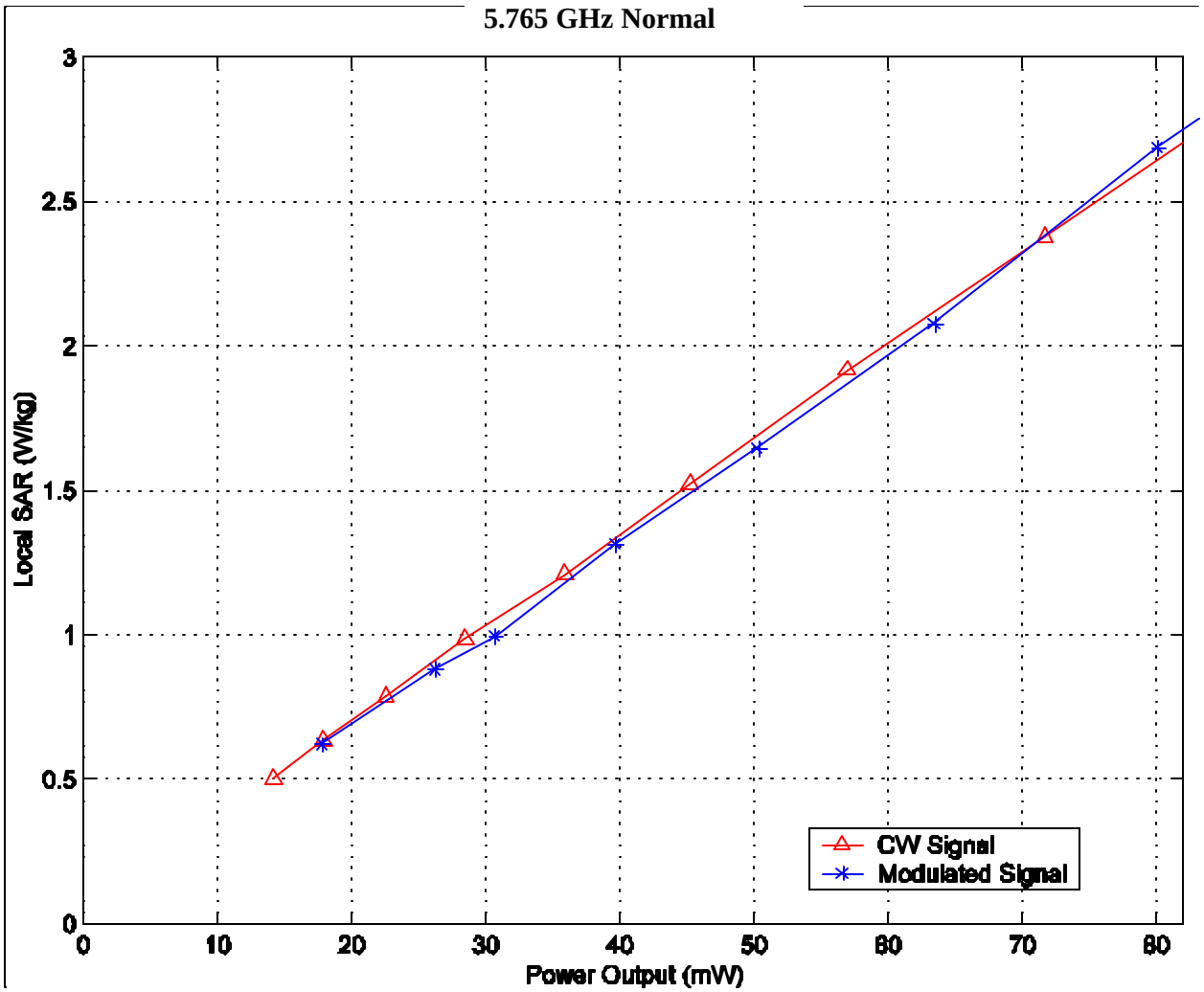


Fig. A.2. Comparison of the SAR for CW or OFDM modulated signals for the normal mode at 5.765 GHz.

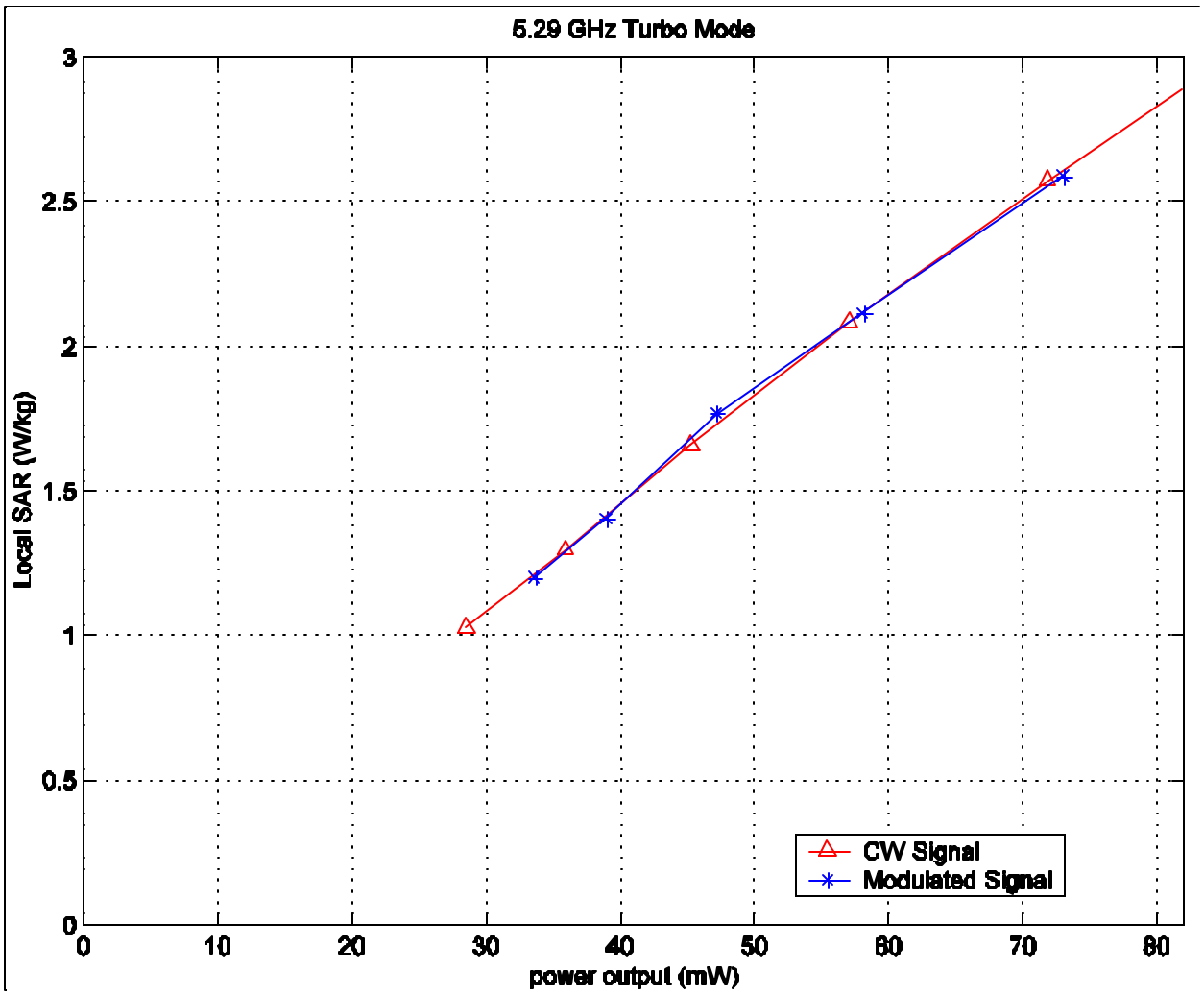


Fig. A.3. Comparison of the SAR for CW or OFDM modulated signals for the turbo mode at 5.29 GHz.

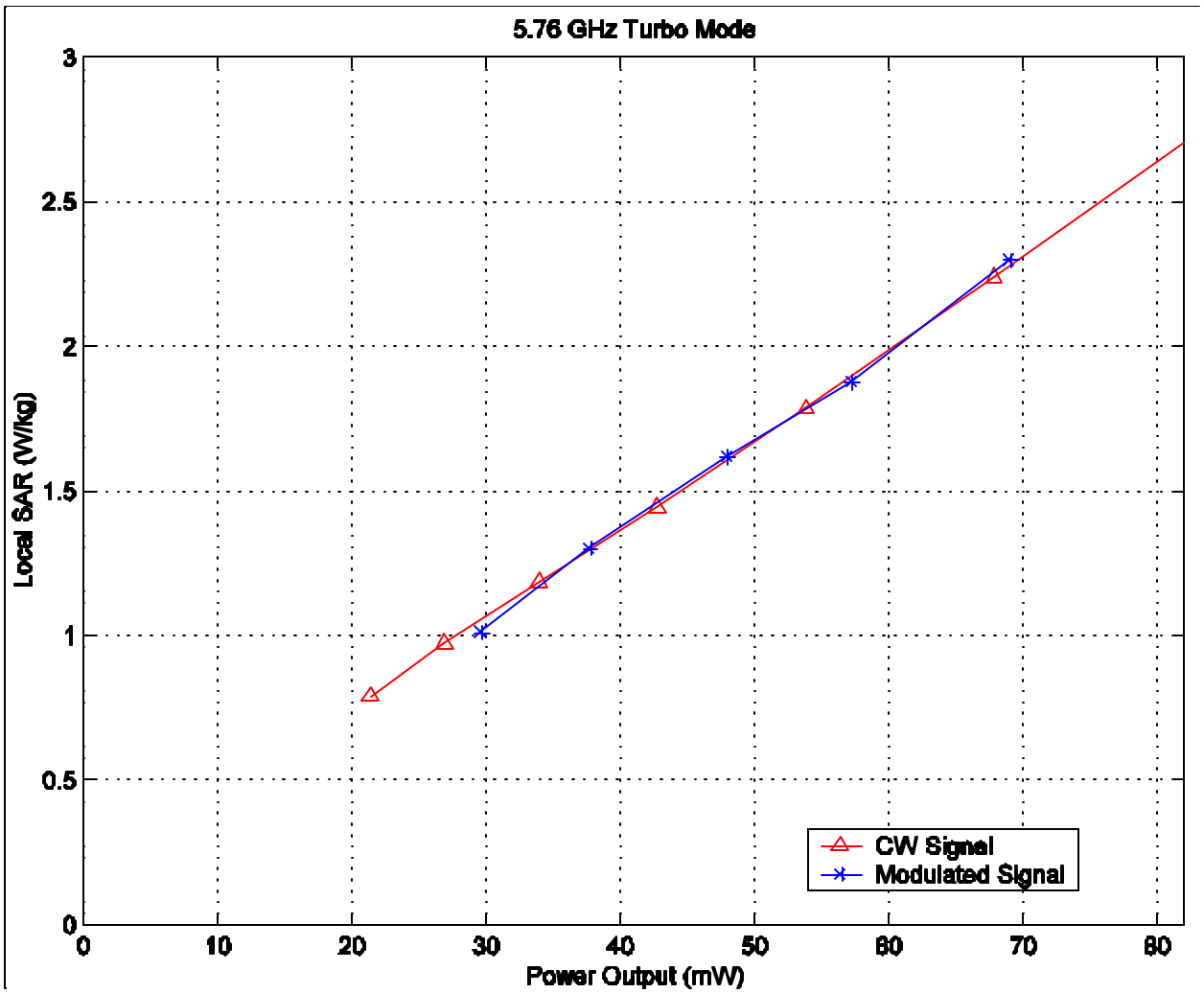


Fig. A.4. Comparison of the SAR for CW or OFDM modulated signals for the turbo mode at 5.76 GHz.

APPENDIX B

SAR System Validation for the 802.11a Band

The measured SAR distribution for the peak 1-g SAR region using WR187 rectangular waveguide radiation system.

For February 13, 2004 – The SAR plot at 5.25 GHz

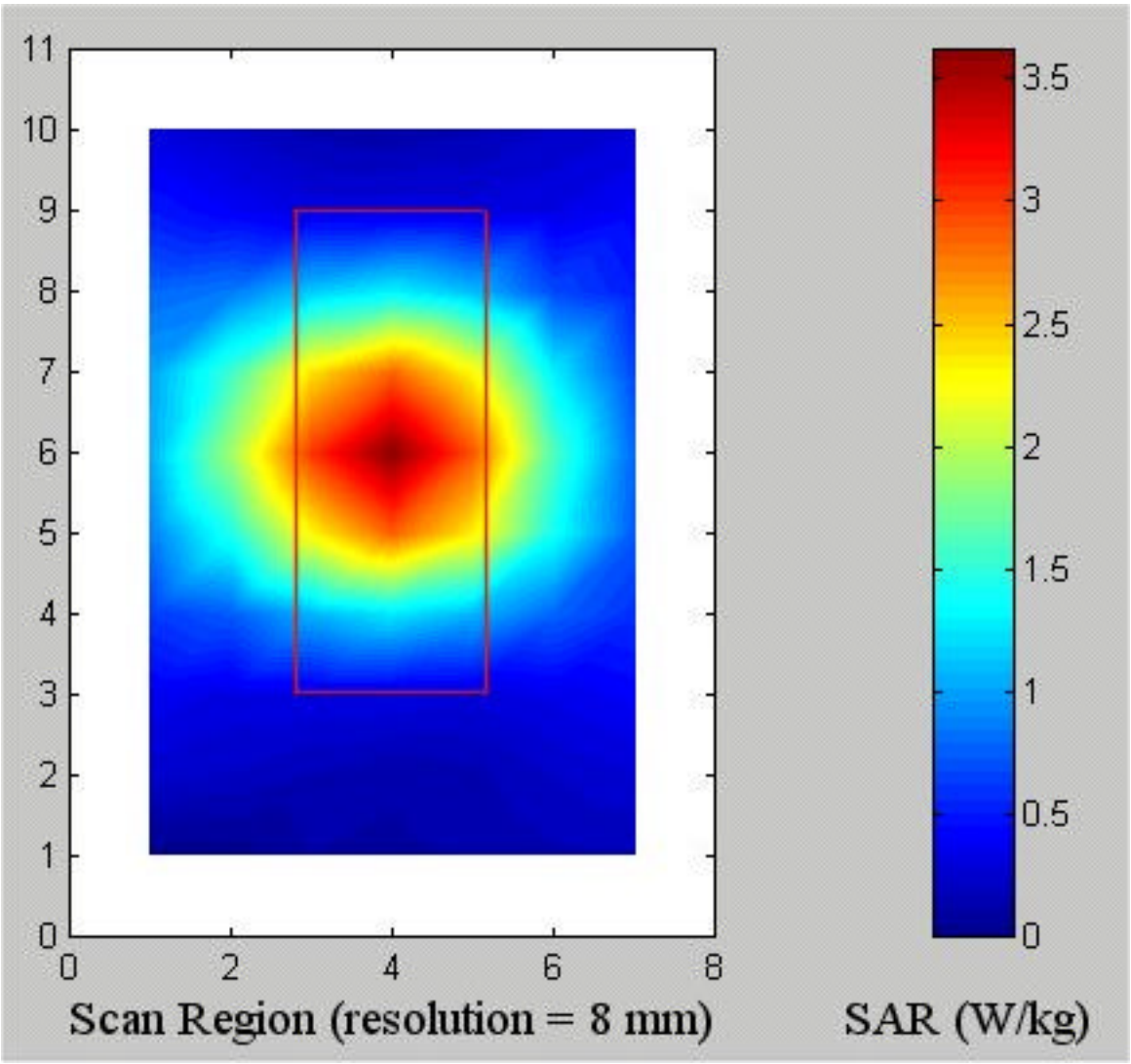


Fig. B.1. Coarse scans of the measured SAR distribution for the WR187 rectangular waveguide irradiation system for system verification at 5.25 GHz. Also shown is the outline of the rectangular waveguide overlaid on the SAR contours. Radiated power = 100 mW.

February 13, 2004

1-g SAR = 3.66 W/kg

a. At depth of 1 mm

8.904	9.720	9.844	9.218	8.598
9.579	10.084	10.442	10.278	9.376
9.877	10.427	10.521	10.418	9.487
9.320	9.958	10.162	9.896	9.273
8.701	9.079	9.594	9.421	8.677

b. At depth of 3 mm

4.373	4.757	4.836	4.608	4.328
4.672	4.997	5.147	5.005	4.643
4.745	5.078	5.202	5.077	4.704
4.546	4.900	5.042	4.865	4.558
4.223	4.520	4.687	4.569	4.255

c. At depth of 5 mm

2.070	2.237	2.292	2.218	2.095
2.185	2.361	2.427	2.339	2.198
2.183	2.357	2.452	2.370	2.231
2.120	2.310	2.390	2.287	2.137
1.946	2.143	2.190	2.122	1.999

d. At depth of 7 mm

1.037	1.114	1.149	1.109	1.046
1.079	1.153	1.191	1.151	1.075
1.066	1.140	1.194	1.160	1.097
1.037	1.138	1.171	1.121	1.040
0.933	1.043	1.073	1.041	0.987

e. At depth of 9 mm

0.597	0.645	0.657	0.615	0.575
0.618	0.637	0.661	0.646	0.587
0.605	0.632	0.658	0.647	0.608
0.587	0.636	0.645	0.628	0.578
0.519	0.570	0.605	0.593	0.563

For February 13, 2004 – The SAR plot at 5.80 GHz

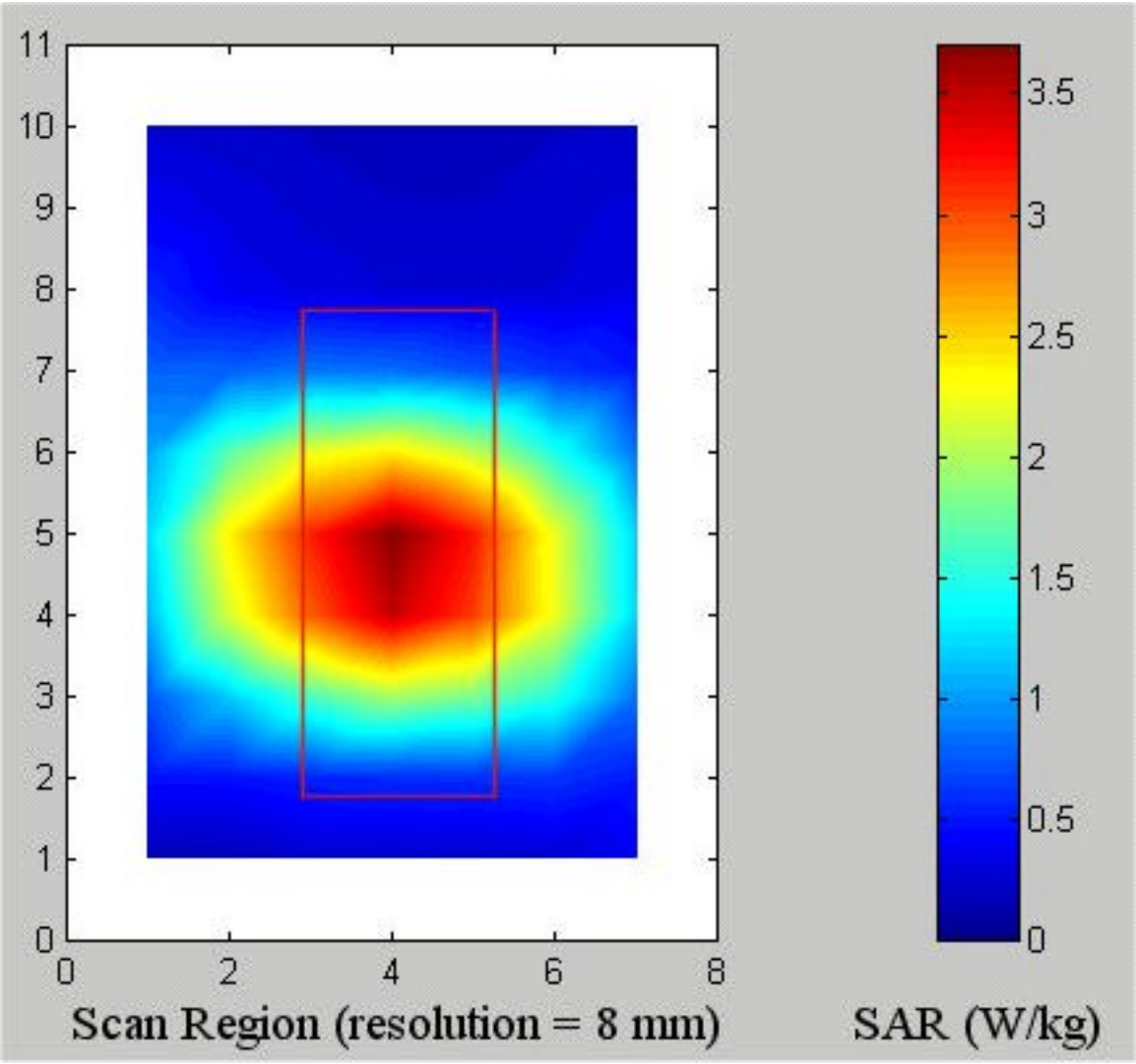


Fig. B.2. Coarse scans of the measured SAR distribution for the WR187 rectangular waveguide irradiation system for system verification at 5.80 GHz. Also shown is the outline of the rectangular waveguide overlaid on the SAR contours. Radiated power = 100 mW.

February 13, 2004

1-g SAR = 4.01 W/kg

a. At depth of 1 mm

10.756	11.410	11.254	11.238	10.631
11.550	11.818	11.947	11.922	11.042
11.839	12.137	12.080	12.040	11.213
11.881	12.087	11.891	11.893	11.462
11.495	11.473	11.805	11.517	11.206

b. At depth of 3 mm

4.725	4.924	4.895	4.873	4.696
5.004	5.153	5.210	5.120	4.847
5.107	5.260	5.285	5.200	4.961
5.123	5.233	5.232	5.158	4.976
4.958	5.019	5.099	5.002	4.835

c. At depth of 5 mm

1.923	1.943	1.960	1.947	1.910
1.988	2.054	2.087	2.010	1.965
2.010	2.075	2.105	2.061	2.014
2.021	2.076	2.107	2.041	1.980
1.952	2.016	2.019	1.995	1.919

d. At depth of 7 mm

0.875	0.856	0.874	0.867	0.846
0.875	0.897	0.917	0.878	0.878
0.875	0.895	0.904	0.904	0.886
0.891	0.906	0.917	0.884	0.869
0.850	0.886	0.887	0.884	0.856

e. At depth of 9 mm

0.552	0.541	0.549	0.538	0.511
0.539	0.551	0.550	0.543	0.533
0.541	0.546	0.539	0.545	0.534
0.564	0.542	0.546	0.536	0.535
0.526	0.538	0.545	0.549	0.539

APPENDIX C

SCREEN DUMPS FOR THE UNIVERSITY OF UTAH TISSUE-SIMULANT FLUID FOR THE FREQUENCY BAND 5.0 TO 6.0 GHz (FIVE REPEATED MEASUREMENTS)

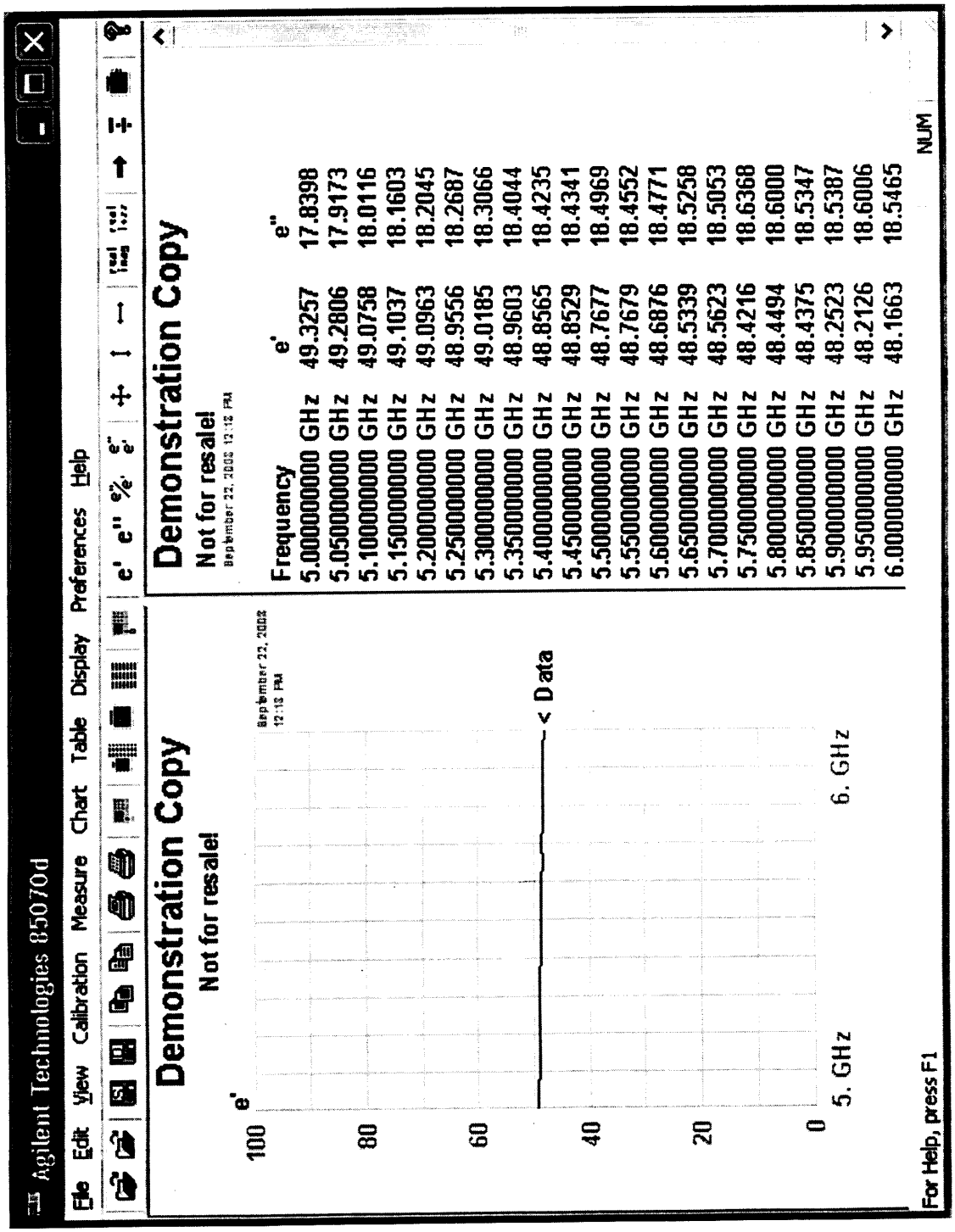
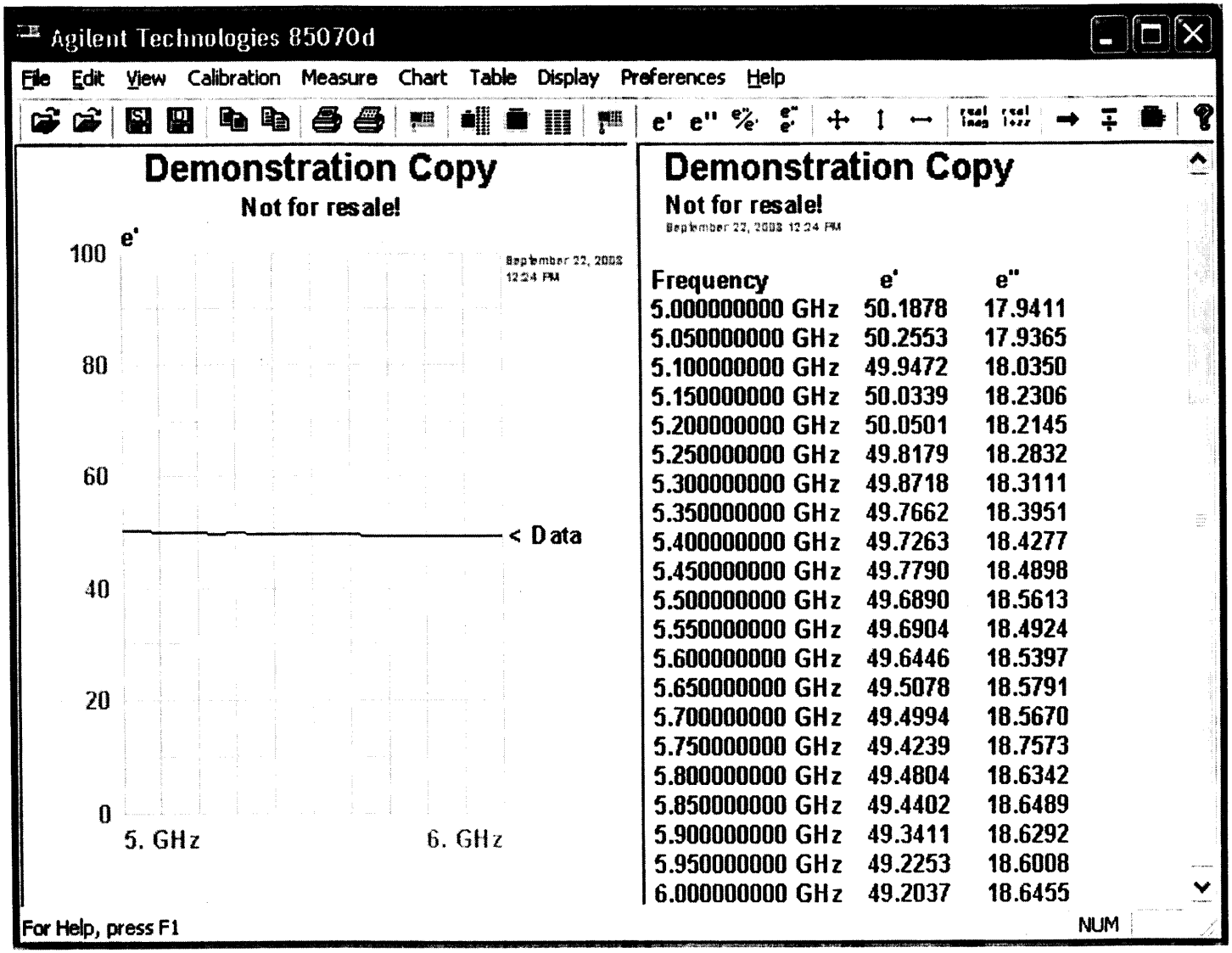
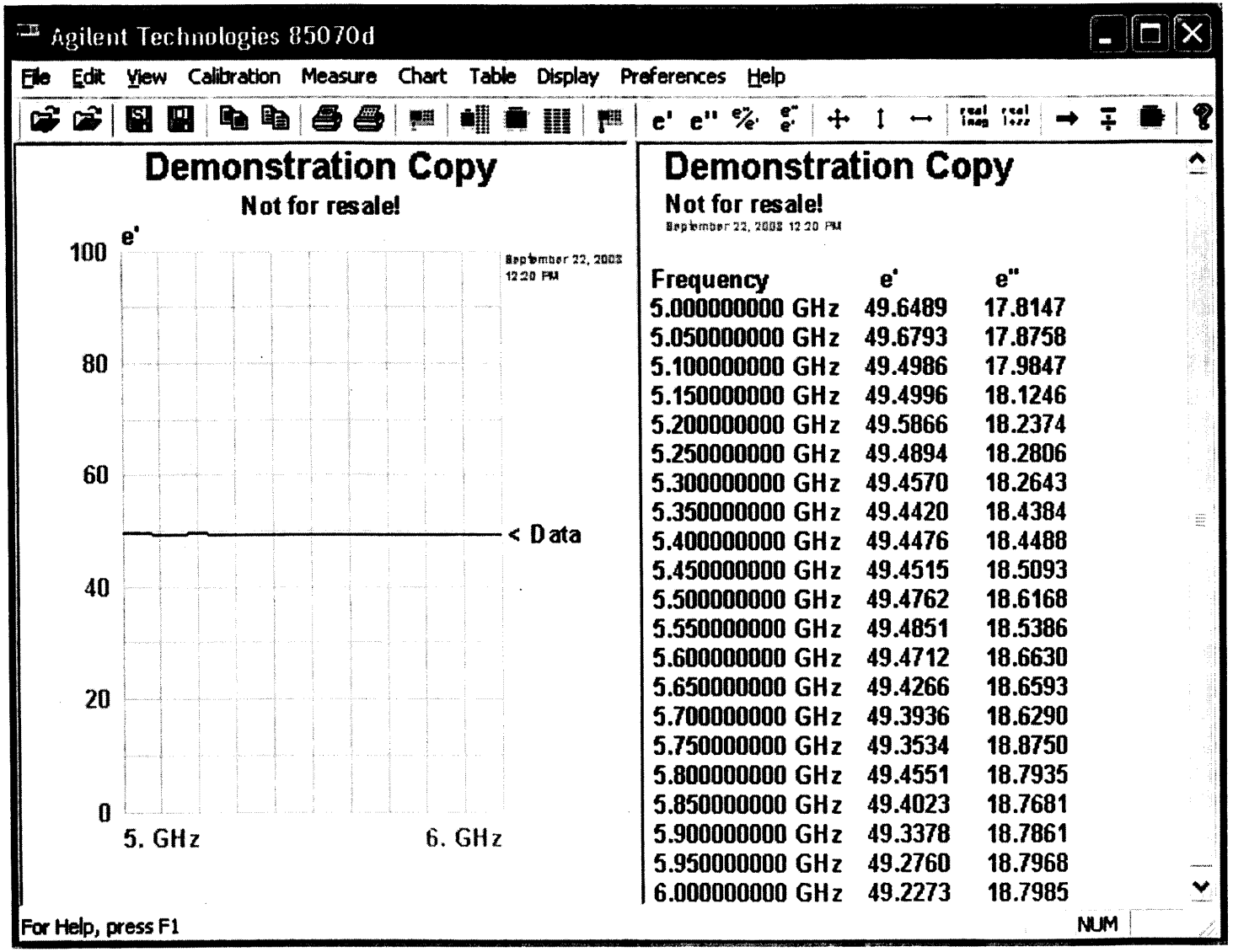


Fig. C.1.



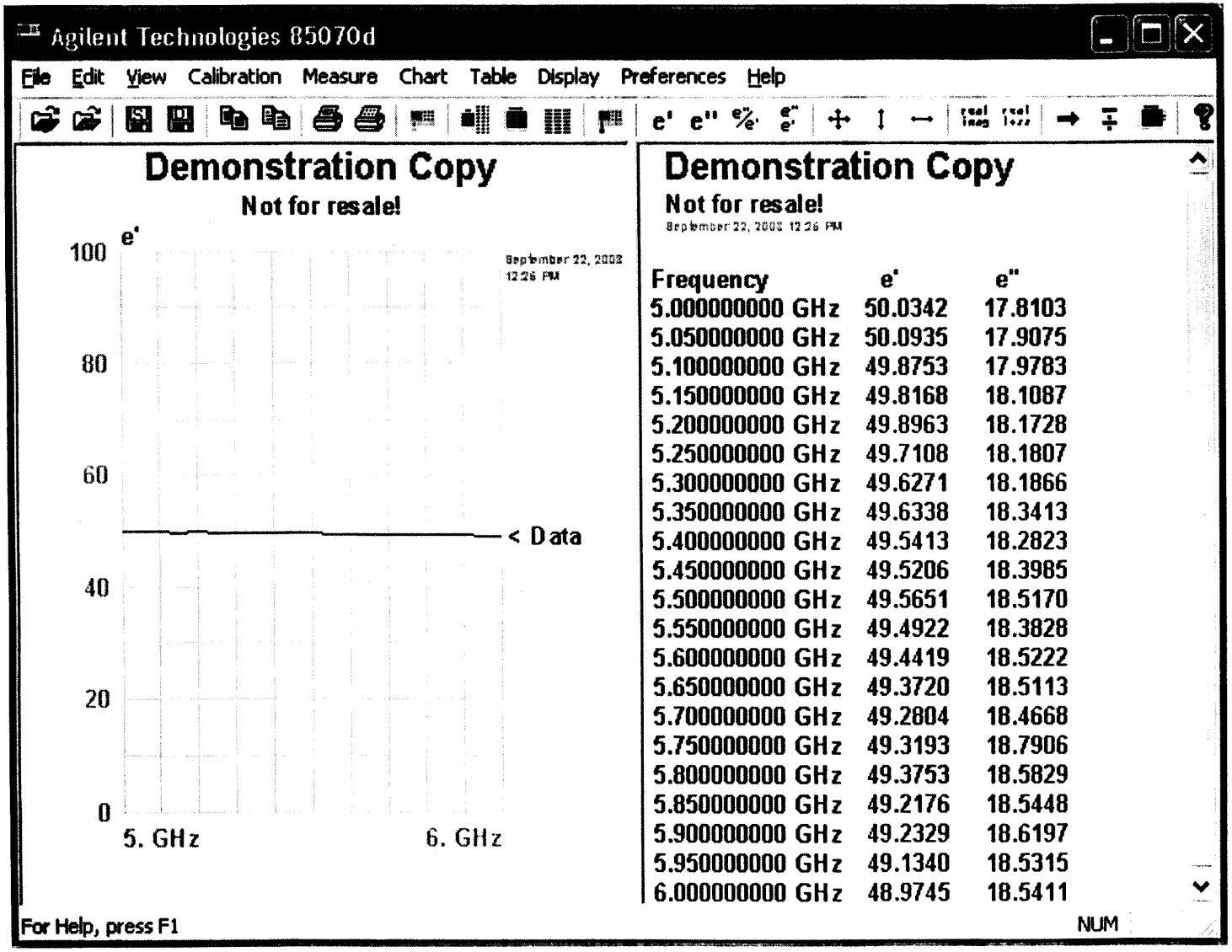
Frequency	e'	e''
5.000000000 GHz	50.1878	17.9411
5.050000000 GHz	50.2553	17.9365
5.100000000 GHz	49.9472	18.0350
5.150000000 GHz	50.0339	18.2306
5.200000000 GHz	50.0501	18.2145
5.250000000 GHz	49.8179	18.2832
5.300000000 GHz	49.8718	18.3111
5.350000000 GHz	49.7662	18.3951
5.400000000 GHz	49.7263	18.4277
5.450000000 GHz	49.7790	18.4898
5.500000000 GHz	49.6890	18.5613
5.550000000 GHz	49.6904	18.4924
5.600000000 GHz	49.6446	18.5397
5.650000000 GHz	49.5078	18.5791
5.700000000 GHz	49.4994	18.5670
5.750000000 GHz	49.4239	18.7573
5.800000000 GHz	49.4804	18.6342
5.850000000 GHz	49.4402	18.6489
5.900000000 GHz	49.3411	18.6292
5.950000000 GHz	49.2253	18.6008
6.000000000 GHz	49.2037	18.6455

Fig. C.2.



Frequency	e'	e''
5.000000000 GHz	49.6489	17.8147
5.050000000 GHz	49.6793	17.8758
5.100000000 GHz	49.4986	17.9847
5.150000000 GHz	49.4996	18.1246
5.200000000 GHz	49.5866	18.2374
5.250000000 GHz	49.4894	18.2806
5.300000000 GHz	49.4570	18.2643
5.350000000 GHz	49.4420	18.4384
5.400000000 GHz	49.4476	18.4488
5.450000000 GHz	49.4515	18.5093
5.500000000 GHz	49.4762	18.6168
5.550000000 GHz	49.4851	18.5386
5.600000000 GHz	49.4712	18.6630
5.650000000 GHz	49.4266	18.6593
5.700000000 GHz	49.3936	18.6290
5.750000000 GHz	49.3534	18.8750
5.800000000 GHz	49.4551	18.7935
5.850000000 GHz	49.4023	18.7681
5.900000000 GHz	49.3378	18.7861
5.950000000 GHz	49.2760	18.7968
6.000000000 GHz	49.2273	18.7985

Fig. C.3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Frequency e' e''
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5.050000000 GHz 50.0935 17.9075
5.100000000 GHz 49.8753 17.9783
5.150000000 GHz 49.8168 18.1087
5.200000000 GHz 49.8963 18.1728
5.250000000 GHz 49.7108 18.1807
5.300000000 GHz 49.6271 18.1866
5.350000000 GHz 49.6338 18.3413
5.400000000 GHz 49.5413 18.2823
5.450000000 GHz 49.5206 18.3985
5.500000000 GHz 49.5651 18.5170
5.550000000 GHz 49.4922 18.3828
5.600000000 GHz 49.4419 18.5222
5.650000000 GHz 49.3720 18.5113
5.700000000 GHz 49.2804 18.4668
5.750000000 GHz 49.3193 18.7906
5.800000000 GHz 49.3753 18.5829
5.850000000 GHz 49.2176 18.5448
5.900000000 GHz 49.2329 18.6197
5.950000000 GHz 49.1340 18.5315
6.000000000 GHz 48.9745 18.5411
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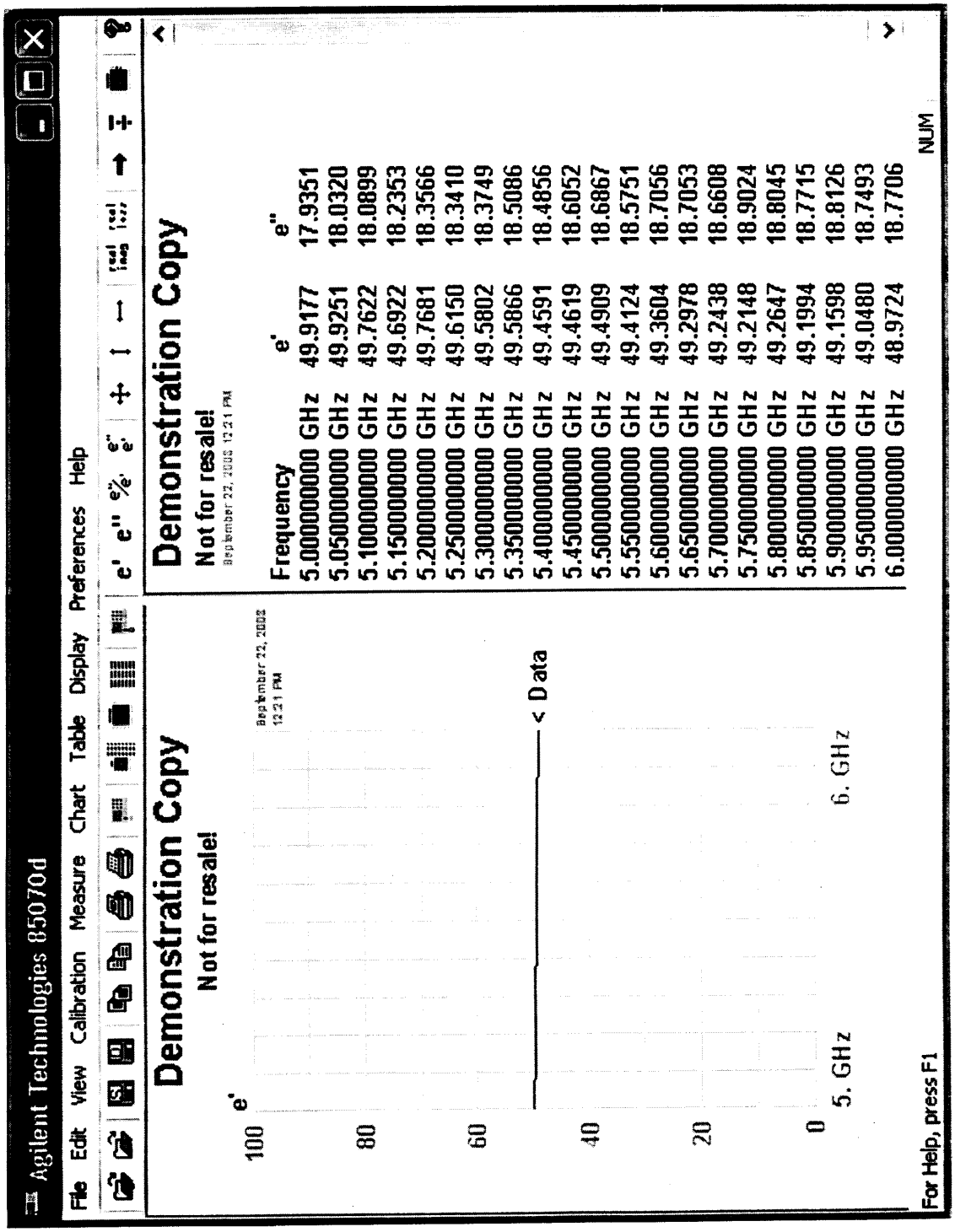
Fig. C.4.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Frequency e' e''
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5.150000000 GHz 49.6922 18.2353
5.200000000 GHz 49.7681 18.3566
5.250000000 GHz 49.6150 18.3410
5.300000000 GHz 49.5802 18.3749
5.350000000 GHz 49.5866 18.5086
5.400000000 GHz 49.4591 18.4856
5.450000000 GHz 49.4619 18.6052
5.500000000 GHz 49.4909 18.6867
5.550000000 GHz 49.4124 18.5751
5.600000000 GHz 49.3604 18.7056
5.650000000 GHz 49.2978 18.7053
5.700000000 GHz 49.2438 18.6608
5.750000000 GHz 49.2148 18.9024
5.800000000 GHz 49.2647 18.8045
5.850000000 GHz 49.1994 18.7715
5.900000000 GHz 49.1598 18.8126
5.950000000 GHz 49.0480 18.7493
6.000000000 GHz 48.9724 18.7706
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Fig. C.5.

APPENDIX D

AN OPEN-ENDED WAVEGUIDE SYSTEM FOR SAR SYSTEM VALIDATION AND/OR PROBE CALIBRATION FOR FREQUENCIES ABOVE 3 GHz

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Abstract

Compliance with safety guidelines prescribed in terms of maximum electromagnetic power absorption (specific absorption rate or SAR) for any 1- or 10-g of tissue is required for all newly-introduced personal wireless devices such as Wi-Fi PCs. The prescribed SAR measuring system is a planar phantom with a relatively thin base of thickness 2.0 mm filled with a lossy fluid to simulate dielectric properties of the tissues. A well-characterized, broadband irradiator is required for SAR system validation and/or submerged E-field probe calibration for the new 802.11a frequencies in the 5-6 GHz band. We describe an open-ended waveguide system that may be used for this purpose. Using a fourth-order polynomial least-square fit to the experimental data gives SAR variations close to the bottom surface of the phantom that are in excellent agreement with those obtained using the FDTD numerical method. The experimentally-determined peak 1-g SARs are within 1 to 2 percent of those obtained using the FDTD both at 5.25 and 5.8 GHz.

Index Terms – Broadband, electromagnetic exposure system, probe calibration, safety assessment, comparison with numerical calculations

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AN OPEN-ENDED WAVEGUIDE SYSTEM FOR SAR SYSTEM VALIDATION AND/OR PROBE CALIBRATION FOR FREQUENCIES ABOVE 3 GHz

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Om P. Gandhi, Life Fellow, IEEE, and
Gang Kang, Senior Member, IEEE

I. Introduction

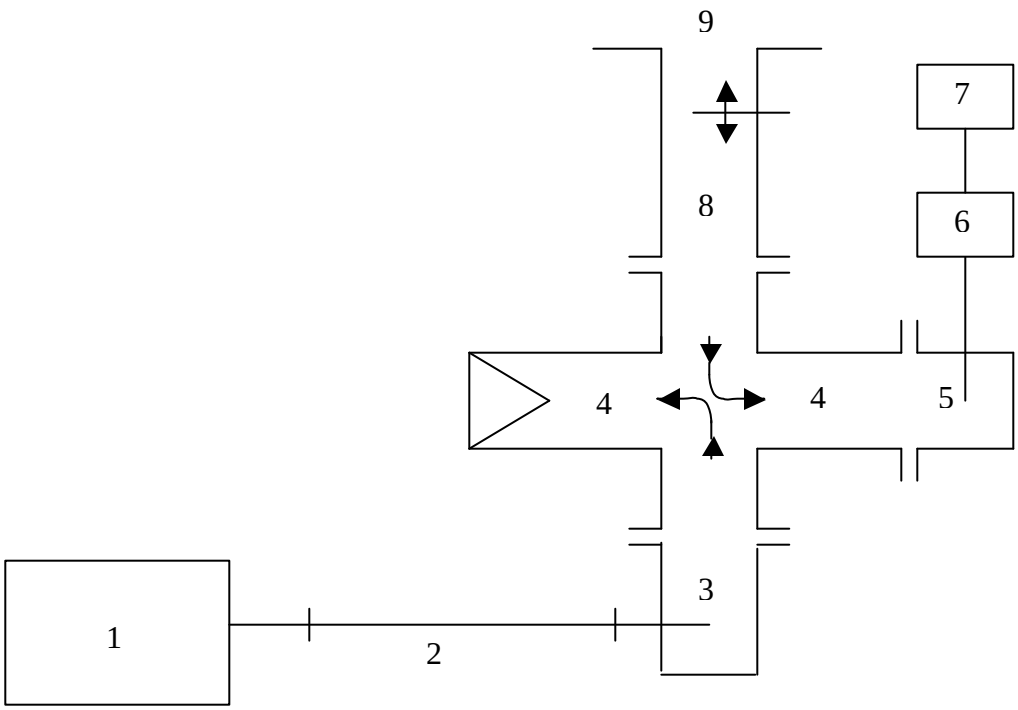
Compliance with the safety guidelines such as those proposed by IEEE [1] ICNIRP [2], etc. is required by regulatory agencies in the United States and elsewhere for all newly-introduced personal wireless devices such as Wi-Fi PCs, cellular telephones, etc. These safety guidelines are set in terms of maximum 1- or 10-g mass-normalized rates of electromagnetic energy deposition (specific absorption rates or SARs) for any 1- or 10-g of tissue. The two most commonly-used SAR limits today are those of IEEE [1] – 1.6 W/kg for any 1 g of tissue, and ICNIRP [2] – 2 W/kg for any 10 g of tissue, excluding extremities such as hands, wrists, feet, and ankles where higher SARs up to 4 W/kg for any 10 g of tissue are permitted in both of these standards. Experimental and numerical techniques using planar or head-shaped phantoms have been proposed for determining compliance with the SAR limits [3-5]. For frequencies above 800 MHz, the size of a rectangular waveguide is quite manageable and use of an appropriate waveguide filled with a tissue-simulant medium is recommended for calibration of an E-field probe in FCC Supplement C, Edition 01-01 to OET Bulletin 65 [6]. Even though no recommendation is made on choice of an irradiation system for frequencies above 3 GHz, balanced half-wave dipoles have been suggested for system validation for frequencies less than or equal to 3 GHz [6]. It is very difficult to develop half-wave dipole antennas for use in the 5.1 to 5.8 GHz band both because of fairly small dimensions and the resulting dimensional tolerances, and relatively narrow bandwidths of the required baluns – balanced to unbalanced transformers (typically less than 10-12% for VSWR < 2.0 and less than 5-6% for VSWR < 1.5). On the other hand, rectangular waveguides are broadband with simultaneous bandwidths larger than 1-2 GHz and are fairly easy to use for frequencies in excess of 3 GHz. We have, therefore, developed an open-ended waveguide system for SAR system validation and/or probe calibration in the frequency band 5 to 6 GHz. This is a band that is presently being used for 802.11a antennas of Wi-Fi PCs.

II. The Waveguide Irradiation System

For the 5-6 GHz band, we have used a WR187 rectangular waveguide of internal dimensions 4.75 × 2.21 cm. The operating (TE_{10} mode) band of this waveguide is from 3.95 to 5.85 GHz. This is considerably larger than the required overall bandwidth of 675 MHz for the IEEE 802.11a frequency bands of 5.15-5.35 and 5.745 to 5.825 GHz. The waveguide irradiation system used for SAR system validation is shown in Fig. 1. As recommended in [6], the open-ended waveguide irradiator is placed at a distance of 8 mm below the base of planar phantom with inside dimensions of 30.5 × 41.9 cm and a base thickness of 2.0 ± 0.2 mm. This results in the open end of the waveguide at a distance of 10 mm below the lossy tissue-simulant fluid in the phantom. The microwave circuit arrangement used for the waveguide irradiation system is shown in Fig. 2. As shown in Fig. 2, the WR187 waveguide is fed with

microwave power from a Hewlett Packard Model 83620A Synthesized Sweeper (10 MHz-20 GHz). When placed at a distance of 8 mm below the base of the planar phantom, the reflection coefficient is about 10-20%. Even this relatively small amount of reflection has been greatly reduced to less than 0.5% by using a movable slide-screw waveguide tuner (Narda Model 22CI). The planar phantom is filled to a depth of 15 cm with a fluid to simulate dielectric properties recommended for the body phantom in [6]. The dielectric constants ε_r and conductivities s at the experimental frequencies of 5.25 and 5.8 GHz are similar to those recommended in the SAR Compliance Standards used in the U.S. and in Europe [3, 4]. For our experiments and calculations, $\varepsilon_r = 48.8$, $\sigma = 6.82$ S/m at 5.25 GHz; and $\varepsilon_r = 46.9$, $\sigma = 7.83$ S/m at 5.8 GHz.

Fig. 1. Photograph of the rectangular waveguide radiator used for system validation. Also seen is the Narda Model 22CI movable slide screw tuner used to match the input power at 5.25 or 5.8 GHz to the planar tissue-simulant phantom.



1. Hewlett Packard (HP) Model 83620A Synthesized Sweeper (10 MHz-20 GHz).
2. Coaxial line.
3. Coaxial to waveguide adapter.
4. 20 dB crossguide coupler (may be reversed to measure incident power).
5. HP Model G281A coaxial to waveguide adapter
6. HP Model 8482A power sensor.
7. HP Model 436A power meter.
8. Narda Microline® Slide Screw Tuner Model 22CI.
9. Radiating open end of the waveguide.

Fig. 2. The microwave circuit arrangement used for SAR system validation.

III. Calculation of the SAR Distributions

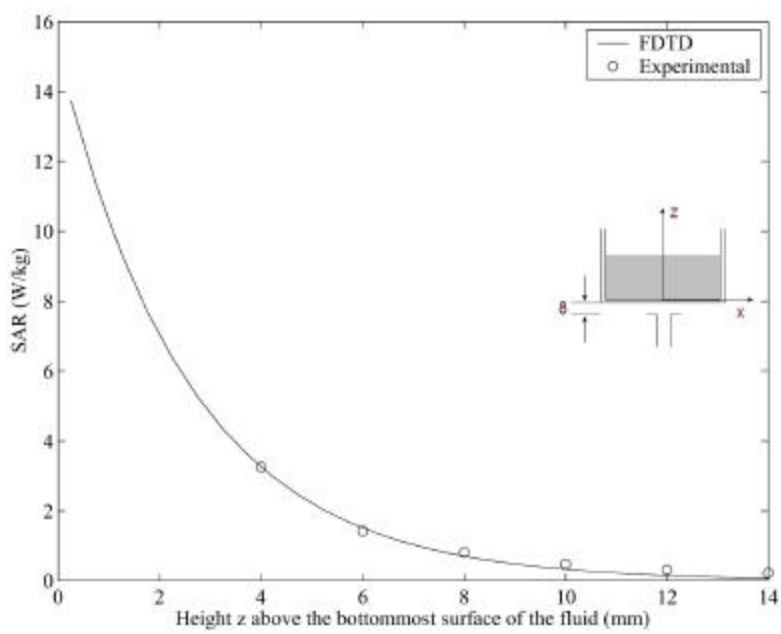
We have used the well-established finite-difference time-domain (FDTD) numerical electromagnetic method to calculate the electric fields and SAR distributions for the planar phantom of base thickness 2.0 mm of dielectric constant $\varepsilon_r = 2.56$ and dielectric properties of the tissue-simulant lossy fluid as given in Section II. The FDTD method described in several texts [7, 8] has been successfully used by various researchers [9-12] and, therefore, would not be described here. For the FDTD calculations, we have used a cell size d = 0.5 mm in order to meet the requirement $\delta \leq \lambda_\varepsilon /10$ in the lossy fluid. The calculated variations of the SAR distribution at the experimental frequencies of 5.25 and 5.80 GHz are given in Figs. 3 a-c and 4 a-c, respectively. Also shown in the

same figures are the experimental values of the SARs (shown by circles). From Figs. 3 and 4, it is obvious that the penetration of electromagnetic fields in the 5.1 to 5.8 GHz band is extremely shallow. The calculated depths of penetration corresponding to $1/e^2$-reduction of SAR (13.5% of the SAR at the surface) are only 6.85 and 5.985 mm at 5.25 and 5.8 GHz, respectively. Both of these depths of penetration are very similar to those obtained for plane-wave irradiation at these frequencies (7.15 mm for 5.25 GHz and 6.25 mm for 5.8 GHz).

IV. Experimental Setup and Measurements

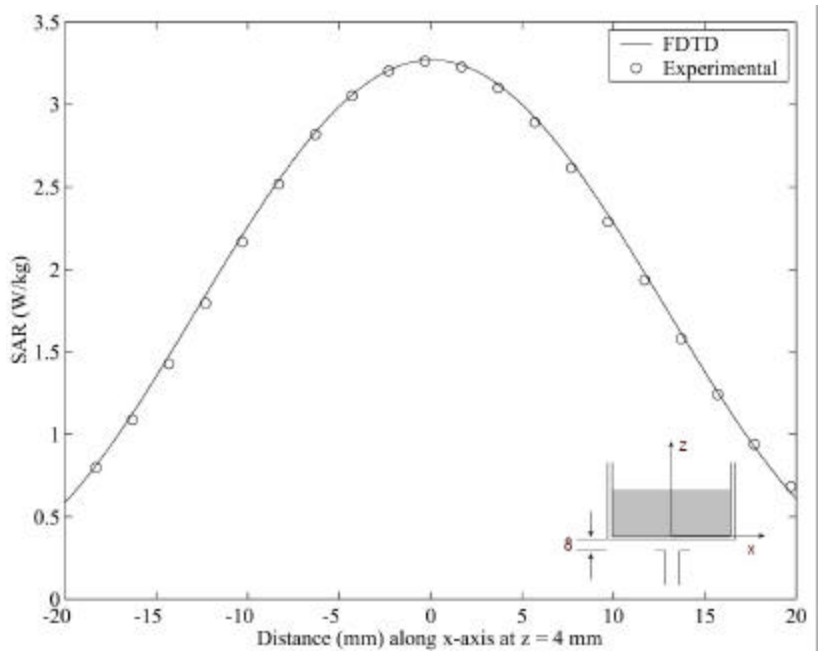
A. Experimental Setup

As recommended in FCC Bulletin 65 [14], a planar phantom of fairly thin base thickness 2.0 mm of relatively low dielectric constant ($\varepsilon_r = 2.56$ in our case) is used for the determination of SAR distributions of wireless PCs and for the SAR system validation. The lateral dimensions of the planar phantom (in our case 30.5 × 41.9 cm) are large enough to ignore scattering from the edges of the rectangular box or the tissue-simulant lossy fluid used to fill this box to a depth of 10-15 cm (several times the depth of penetration of fields in the fluid so as to present a nearly infinitely deep medium to neglect reflections). A photograph of the phantom model together with a computer-controlled 3-D stepper motor system (Arrick Robotics MD-2A) is shown in Fig. 5.

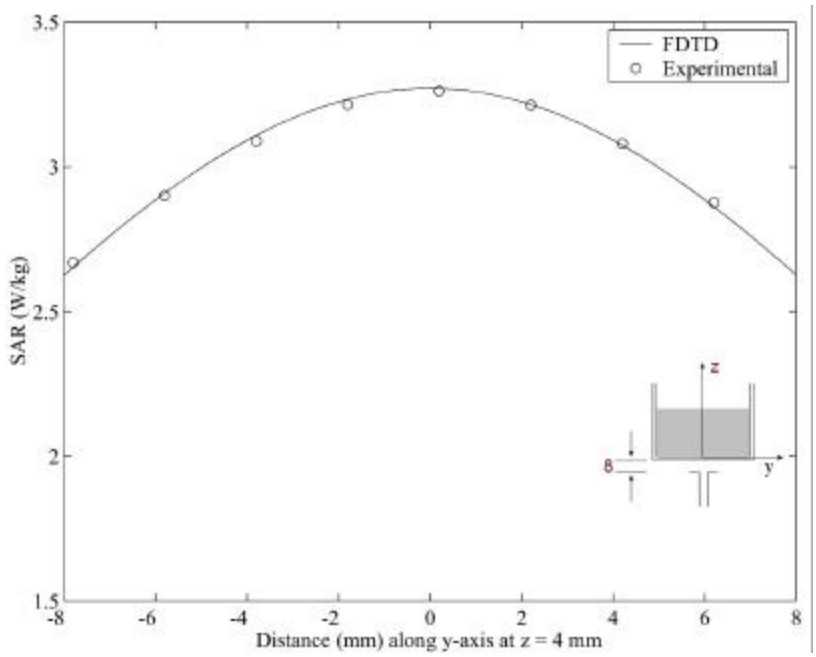


a. Variation of SAR along the z-axis.

Fig. 3. Comparison of the measured and calculated SAR variations for a planar phantom of base thickness 2.0 mm and internal dimensions 30.5 × 41.9 × 20 cm for a WR 187 open-ended waveguide radiator placed 10 mm below the bottommost surface of the lossy tissue-simulant phantom. Frequency = 5.25 GHz.

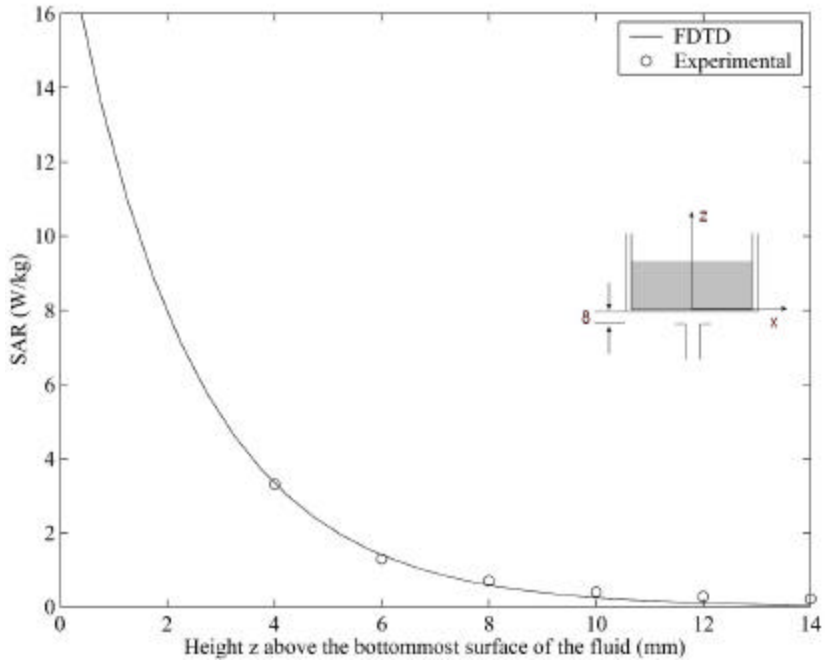


b. Variation of SAR along the x-axis parallel to the broader dimension of the waveguide at height z = 4 mm.

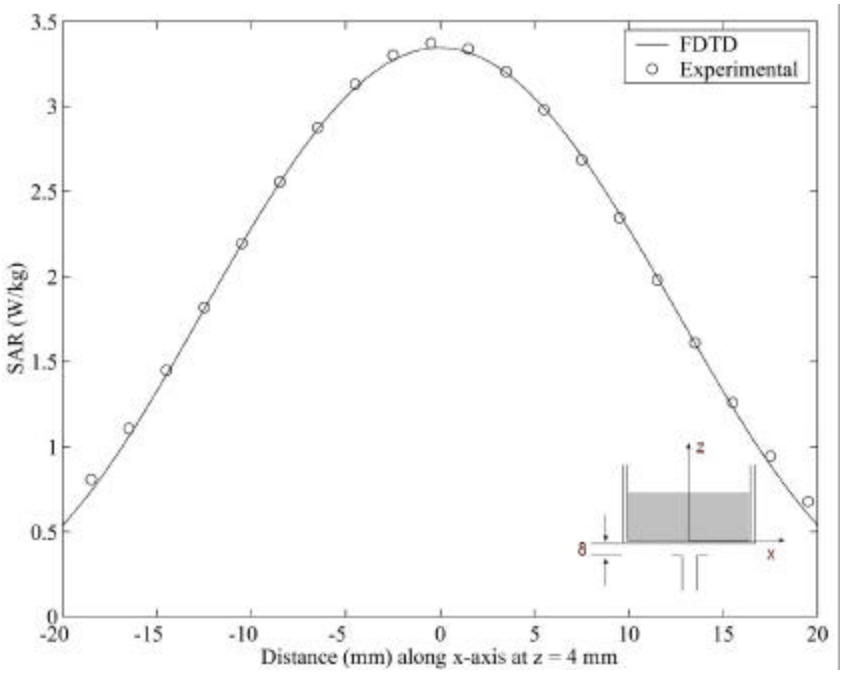


c. Variation of SAR along the y-axis parallel to the narrower dimension of the waveguide at height z = 4 mm.

Fig. 3. Comparison of the measured and calculated SAR variations for a planar phantom of base thickness 2.0 mm and internal dimensions 30.5 × 41.9 × 20 cm for a WR 187 open-ended waveguide radiator placed 10 mm below the bottommost surface of the lossy tissue-simulant phantom. Frequency = 5.25 GHz.

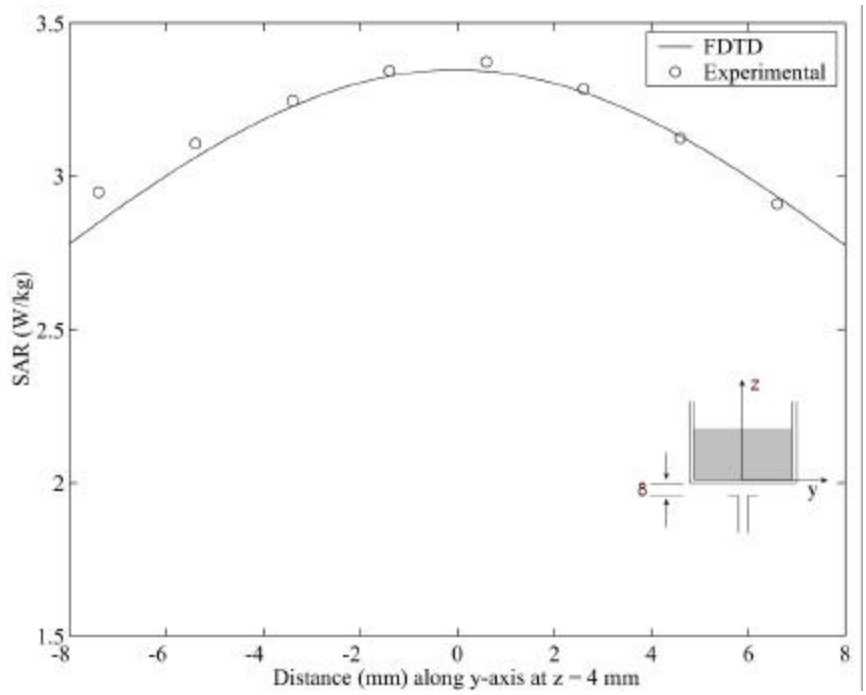


a. Variation of SAR along the z-axis.



b. Variation of SAR along the x-axis parallel to the broader dimension of the waveguide at height z = 4 mm.

Fig. 4. Comparison of the measured and calculated SAR variations for a planar phantom of base thickness 2.0 mm and internal dimensions 30.5 × 41.9 × 20 cm for a WR 187 open-ended waveguide radiator placed 10 mm below the bottommost surface of the lossy tissue-simulant phantom. Frequency = 5.8 GHz.



c. Variation of SAR along the y-axis parallel to the narrower dimension of the waveguide at height z = 4 mm.

Fig. 4. Comparison of the measured and calculated SAR variations for a planar phantom of base thickness 2.0 mm and internal dimensions 30.5 × 41.9 × 20 cm for a WR 187 open-ended waveguide radiator placed 10 mm below the bottommost surface of the lossy tissue-simulant phantom. Frequency = 5.8 GHz.

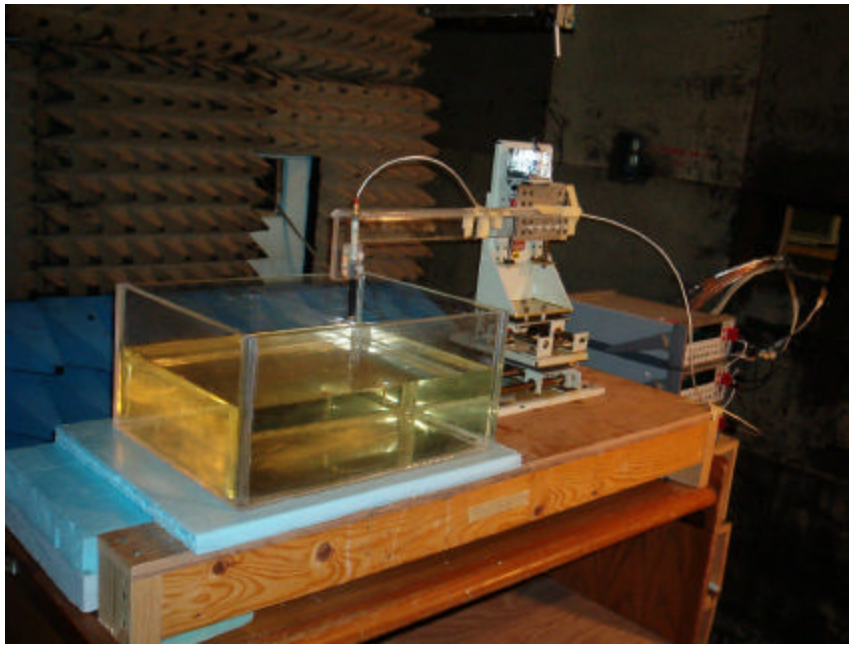


Fig. 5. Photograph of the planar model with the 3-D stepper motor system used for measurement of SAR variation for comparison with FDTD calculations.

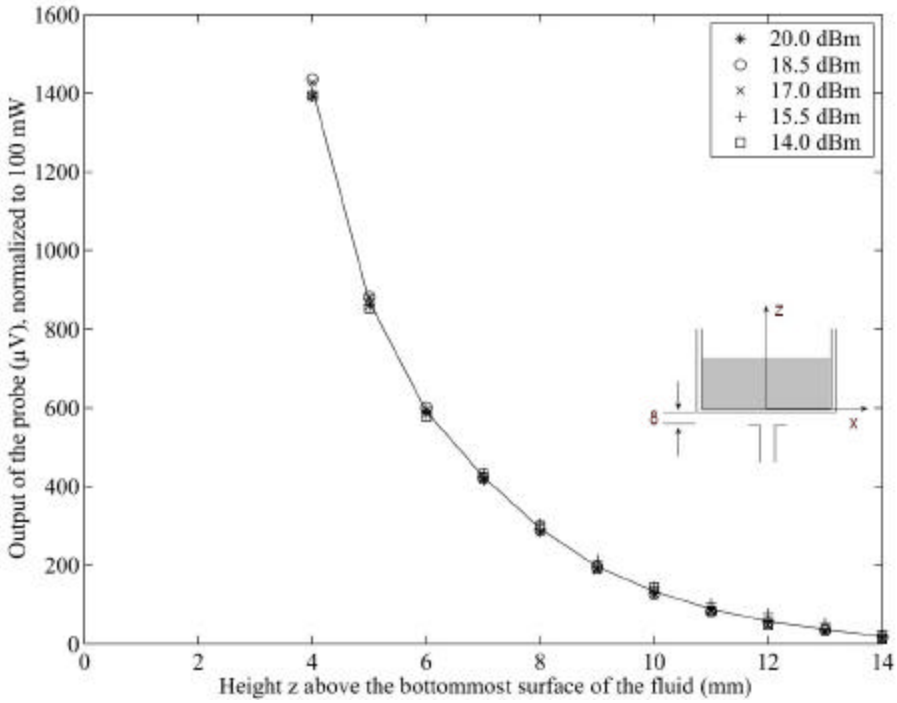
A triaxial Narda Model 8021 E-field probe is used to determine the internal electric fields. The positioning repeatability of the stepper motor system moving the E-field probe is within ± 0.1 mm. Outputs from the three channels of the E-field probe are dc voltages, the sum of which is proportional to the square of the internal electric fields $(|E_i|^2)$ from which the SAR can be obtained from the equation: SAR = $\sigma(|E_i|^2)/\rho$, where σ and ρ are the conductivity and mass density of the tissue-simulant material, respectively [13]. The dc voltages for the three channels of the E-field probe are read by three HP 34401A multimeters and sent to the computer via an HPIB interface. The setup is carefully grounded and shielded to reduce the noise due to the electromagnetic interference (EMI).

B. E-Field Probe

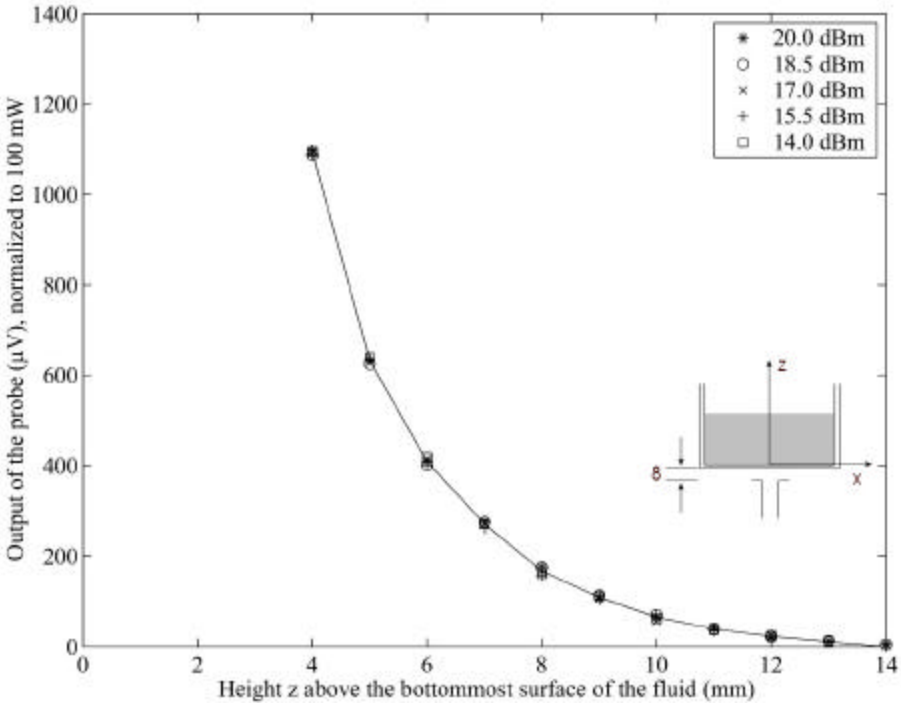
The nonperturbing implantable E-field probe used in the setup was originally developed by Bassen et al. [14] and is manufactured by L3/Narda Microwave Corporation, Hauppauge, NY as Model 8021 E-field probe. In the probe, three orthogonal miniature dipoles each of length approximately 2.5 mm are placed on a triangular-beam substrate. Each dipole is loaded with a small Schottky diode and connected to the external circuitry by high resistance ($2\ M\Omega \pm 40\%$) leads to reduce secondary pickups. The entire structure is then encapsulated with a low dielectric constant insulating material. The probe thus constructed has a very small diameter (4 mm), which results in a relatively small perturbation of the internal electric field. The probe is rated for frequencies up to 3 GHz for tissue-simulant media, but is presently used for system validation at frequencies in the 5 to 6 GHz range. Consequently, the probe had to be checked for square-law performance, and isotropy for use at these higher frequencies.

1. **Test for Square-Law Region:** It is necessary to operate the E-field probe in the square-law region for each of the diodes so that the sum of the dc voltage outputs from the three dipoles is proportional to the square of the internal electric field $(|E_i|^2)$. Fortunately, the personal wireless devices such as the PCs induce SARs that are generally less than 5-6 W/kg even for closest locations to the body. For SAR measurements, it is, therefore, necessary that the E-field probe be checked for square-law behavior for SARs up to such values that are likely to be encountered. Such a test may be conducted using a canonical lossy body such as a rectangular box used here. By varying the radiated power of the waveguide, the output of the probe should increase linearly with the applied power for each of the test locations.

   Shown in Fig. 6a and b are the results of the tests performed to check the square-law behavior of the E-field probe used in our setup at 5.25 and 5.8 GHz, respectively. Used as the radiator is the WR 187 waveguide placed at a distance of 8 mm below the base of the planar phantom (10 mm below the bottom surface of the tissue-simulant fluid as recommended in [6]).



a. Test for square-law behavior at 5.25 GHz.



b. Test for square-law behavior at 5.8 GHz.

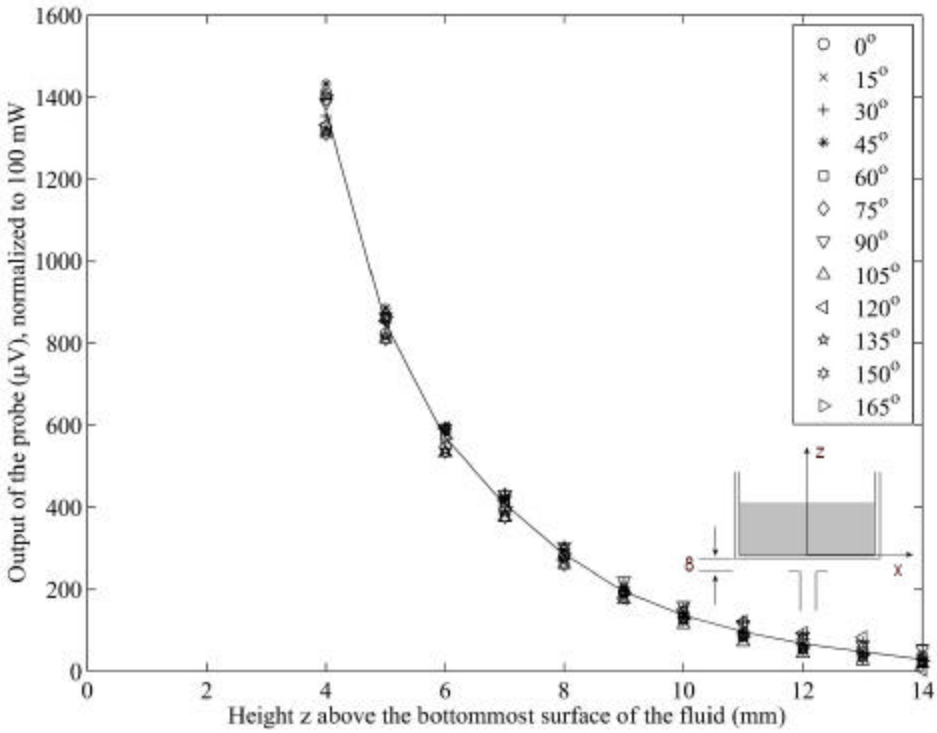
Fig. 6. Variation of the output voltage (proportional to $|E_i|^2$) for different radiated powers normalized to 100 mW (20 dBm).

Since the dc voltage outputs of the probe are fairly similar when normalized to a radiated power of 100 mW, the square-law behavior is demonstrated and an output voltage that is proportional to $|E_i|^2$ is obtained within ± 2.2% both at 5.25 and 5.8 GHz.

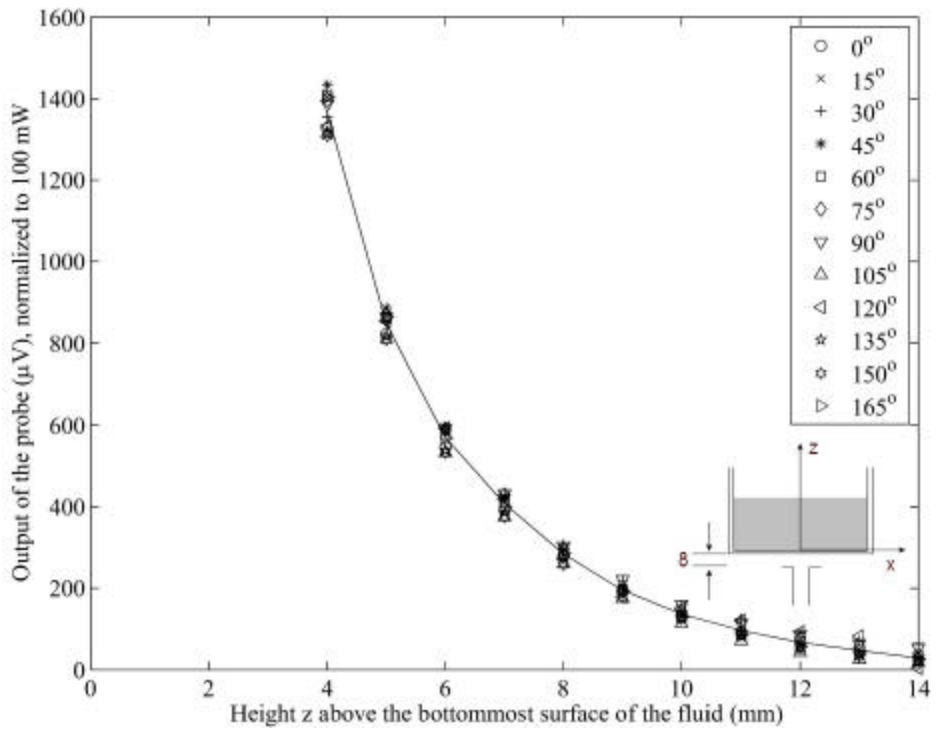
2. **Test for Isotropy of the Probe:** Another important characteristic of the probe that affects the measurement accuracy is its isotropy. Since the orientation of the induced electric field is generally unknown, the E-field probe should be relatively isotropic in its response to the orientation of the E-field. Shown in Fig. 7a and b are the test results of the E-field probe used in our setup at 5.25 and 5.8 GHz, respectively. The E-field probe was rotated around its axis from 0-180° in incremental steps of 15°. Because of the alternating nature of the fields, angles of θ and 180° + θ are identical, hence 0-165° rotation of the E-field probe was considered to be adequate to cover the entire 360° rotation of the probe. As seen in Fig. 7a and b, an isotropy of less than ± 0.18 dB (± 4.3%) was observed for this E-field probe both at 5.25 and 5.8 GHz.

3. **Calibration of the E-Field Probe:** Since the voltage output of the E-field probe is proportional to the square of the internal electric field ($|E_i|^2$), the SAR is, therefore, proportional to the voltage output of the E-field probe by a proportionality constant C. The constant C is defined as the calibration factor and is frequency and material dependent. It is measured to calibrate the probe at the various frequencies of interest using the appropriate tissue-simulating materials for the respective frequencies.

   Canonical geometries such as waveguides, rectangular slabs, and layered or homogeneous spheres have, in the past, been used for the calibration of the implantable E-field probe [15-17] albeit at lower frequencies. Since the FDTD method has been carefully validated to solve electromagnetic problems for a variety of near-field exposure geometries [18], we were able to calibrate the Narda E-field probe by comparing the measured variations of the probe voltage (proportional to $|E_i|^2$) against the FDTD-calculated variations of the SARs for the planar phantom of base thickness 2.0 mm ($\varepsilon_r = 2.56$) and internal dimensions 30.5 × 41.9 × 20 cm irradiated by the WR 187 waveguide placed below this phantom as previously described in Section. II. Shown in Figs. 6a, b and 7a, b are the comparisons between the experimentally measured and FDTD-calculated variations of the SAR distributions in the tissue-simulant fluid. Since there are excellent agreements between the calculated SARs and the measured variations of the voltage outputs of the E-field probe, it is possible to calculate the calibration factors at the respective frequencies by fitting the measured data to the FDTD-calculated results by means of the least mean-square error (LMSE) method. For the Narda Model 8021 E-field probe used in our setup, the calibration factor is determined to be 2.98 (mW/kg)/μV ± 5% both at 5.25 and 5.8 GHz, respectively.



a. 5.25 GHz.



b. 5.8 GHz.

Fig. 7. Test for isotropy.

IV. Need for Extrapolation

Because of the physical separation of the three orthogonal pickup dipoles from the tip of the E-field probe, the SAR measurements cannot be taken any closer than about 3 mm from the bottom surface of the phantom fluid. As given in Figs. 8 and 9, we have measured the SARs with 2 mm resolution at heights of 4, 6, 8, 10, 12 and 14 mm above the bottom surface of the phantom fluid. We have tried second-, third-, fourth-, and fifth-order polynomial least-square fits to extrapolate the measured data to obtain SARs closer to the bottom of the lossy fluid. As seen in Figs. 8 and 9, the second- and third-order polynomials underestimate the SARs while the fifth-order polynomial overestimates the SAR distribution. An excellent least-square fit to the numerically-calculated SAR variations is obtained by using a fourth-order polynomial to extrapolate the measured data both at 5.25 and 5.8 GHz.

After identifying the region of the highest SAR, the SAR distributions were measured with a finer resolution of 2 mm in order to obtain the peak $1 cm^3$ or 1-g SAR. Here too, the SAR measurements were performed for the xy planes at heights z of 4, 6, 8, 10, 12, and 14 mm from the bottom surface of the body-simulant fluid. The SARs thus measured were extrapolated using a fourth-order least-square fit to the measured data to obtain values at 1, 3, 5, 7, and 9 mm height and used to obtain peak 1-g SARs. For a radiated power of 100 mW, the SARs thus obtained with 2 mm resolution for xy planes at heights z of 1, 3, 5, 7, and 9 mm for the peak SAR region of volume 10 ×10 × 10 mm were used to obtain peak 1-g SAR at 5.25 and 5.8 GHz, respectively. The experimentally-determined peak 1-g SARs for 100 mW of radiated power of 3.678 and 3.947 W/kg are extremely close to the FDTD-calculated 1-g SARs for this waveguide irradiator of 3.580 and 3.946 W/kg at 5.25 and 5.80 GHz, respectively.

V. Conclusions

We have developed an open-ended waveguide irradiation system for validation of the SAR measurement system and/or for E-field probe calibration in the 802.11a frequency band 5.15 to 5.825 GHz. A fourth-order polynomial least-square fit to the experimental data gives SAR variations close to the bottom surface of the phantom that are in excellent agreement with those obtained using the FDTD method. The experimentally-determined peak 1-g SARs are within 1 to 2 percent of those obtained using the FDTD numerical calculations.

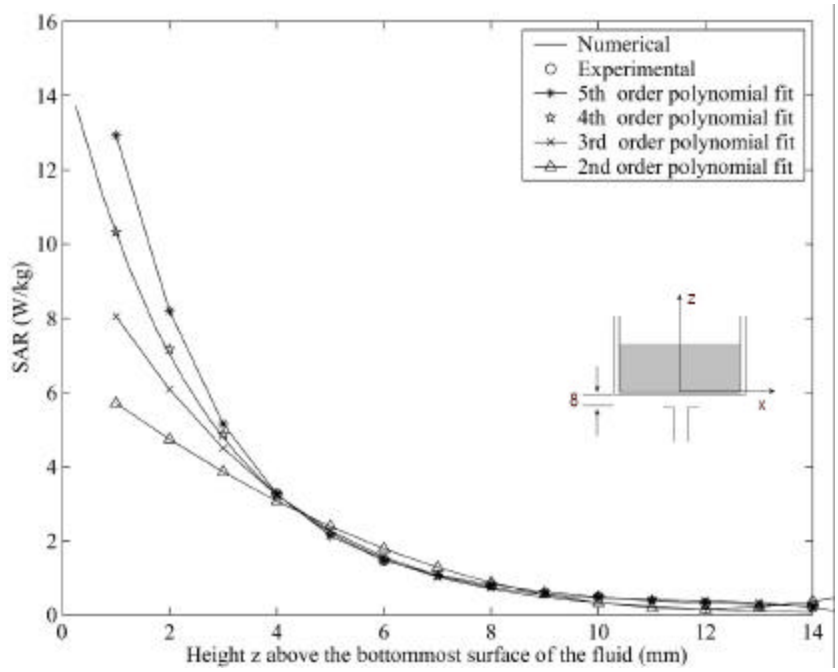


Fig. 8. Comparison of the experimentally measured and FDTD-calculated variation of the SAR with depth in the body-simulant planar phantom at 5.25 GHz. Also shown are the SARs extrapolated from experimental values to heights of 1, 3, 5, 7 and 9 mm above the bottom of the phantom using second-, third-, fourth-, and fifth-order least-square fit polynomials.

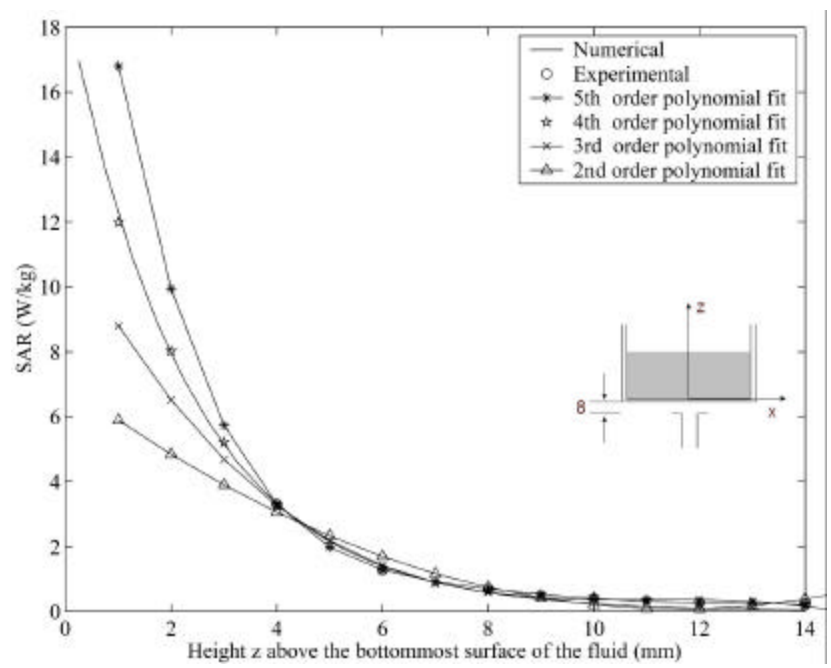


Fig. 9. Comparison of the experimentally measured and FDTD-calculated variation of the SAR with depth in the body-simulant planar phantom at 5.8 GHz. Also shown are the SARs extrapolated

from experimental values to heights of 1, 3, 5, 7 and 9 mm above the bottom of the phantom using second-, third-, fourth-, and fifth-order least-square fit polynomials.

REFERENCES

1. IEEE Std. C95.1, "IEEE Standard for Safety Levels with Respect to Human Exposure to Radiofrequency Electromagnetic Fields, 3 kHz to 300 GHz," Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1999.

2. ICNIRP (International Commission on Non-Ionizing Radiation Protection), "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)", *Health Physics*, Vol. 74, pp. 494-522, 1998.

3. IEEE Standards Coordinating Committee 34 Draft Standard, "Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body Due to Wireless Communications Devices: Experimental Techniques," Institute of Electrical and Electronics Engineers, 2002.

4. CENELEC EN50361, "Basic Standard for Measurement of Specific Absorption Rate Related to Human Exposure to Electromagnetic Fields from Mobile Telephones (300-MHz-3 GHz), CENELEC European Committee for Electrotechnical Standardization, rue de Stassart 35, B-1050, Brussels, Belgium.

5. IEC TC 106/PT62209, "Evaluation of Human Exposure to Radiofrequency Fields from Handheld and Body-Mounted Wireless Communications Devices in the Frequency Range of 30 MHz to 6 GHz: Human Models, Instrumentation Procedures," Draft Standard in preparation, 2003.

6. U.S. Federal Communications Commission (FCC), "Additional Information for Evaluating Compliance of Mobile and Portable Devices with FCC Limits for Human Exposure to Radiofrequency Emissions," Supplement C Edition 01-01 to OET Bulletin 65 Edition 97-01, June 2001.

7. A. Taflove (Ed.), *Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Boston, MA, 1998.

8. A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Boston, MA, 2000.

9. P. J. Dimbylow and S. M. Mann, "SAR Calculations in an Anatomically-Based Realistic Model of the Head for Mobile Communication Transceivers at 900 MHz and 1.8 GHz," *Physics in Med. And Biol.*, Vol. 39, pp. 1537-1553, 1994.

10. O. P. Gandhi and J. Y. Chen, "Electromagnetic Absorption in the Human Head from Experimental 6 GHz Handheld Transceivers," *IEEE Trans. On Electromag. Compat.*, Vol. 37, pp. 547-558, 1995.

11. M. A. Jensen and Y. Rahmat-Samii, "EM Interaction in Handset Antennas and a Human in Personal Communications," *Proc. IEEE,* Vol. 83, pp. 7-17, 1995.

12. M. Okoniewski and M. A. Stuchly, "A Study of Handset Antenna and Human Body Interaction, *IEEE Trans. On Microwave Theory and Tech,* Vol.. 44, pp. 1855-1864, 1996.

13. M. A. Stuchly and S. S. Stuchly, "Experimental Radio and Microwave Dosimetry, " in *Handbook of Biological Effects of Electromagnetic Fields,*, 2nd ed., C. Polk and E. Postow, Eds. Boca Raton, FL: CRC, pp. 295-336, 1996.

14. H. I. Bassen and G. S. Smith, "Electric Field Probes – a Review," *IEEE Trans. Antennas Propagat.,* Vol. AP-31, pp. 710-718, September 1983.

15. D. Hill, "Waveguide Techniques for the Calibration of Miniature Electric Field Probes for Use in Microwave Bioeffects Studies," *IEEE Trans. Microwave Theory Tech.,* Vol. MTT-30, pp. 92-94, 1982.

16. N. Kuster and Q. Balzano, "Energy Absorption Mechanism by Biological Bodies in the Near Field of Dipole Antennas Above 300 MHz," *IEEE Trans. Veh. Technol.,* Vol. 41, pp. 17-23, February 1992.

17. M. A. Stuchly, S. S. Stuchly, and A. Kraszewski, "Implantable Electric Field Probes – Some Performance Characteristics," *IEEE Trans. Biomed. Eng.,* Vol. BME-31, pp. 526-531, July 1984.

18. C. M. Furse, Q. S. Yu, and O. P. Gandhi, "Validation of the Finite-Difference Time-Domain Method for Near-Field Bioelectromagnetic Simulations," *Microwave and Optical Technology Letters,* Vol. 16, pp. 341-345, 1997.

APPENDIX E

Uncertainty Analysis

The uncertainty analysis of the University of Utah SAR Measurement System is given in Table E.1. Several of the numbers on tolerances are obtained by following procedures similar to those detailed in [3], while others have been obtained using methods suggested in [5].

Table E.1. Uncertainty analysis of the University of Utah SAR Measurement System.

Uncertainty Component	Uncertainty Value ± %	Probability Distribution	Divisor	C_i 1-g	Standard Unc. u_i ± %	ν_i
Measurement System						
Probe calibration	2.0	N	1	1	2.0	∞
Axial isotropy of the probe	4.0	R	√3	$(1\text{-}cp)^{1/2}$	1.6	∞
Hemispherical isotropy of the probe	5.5	R	√3	$\sqrt{c_p}$	0.0	∞
Boundary effect	0.8	R	√3	1	0.5	∞
Probe linearity	3.0	R	√3	1	1.7	∞
System detection limits	1.0	R	√3	1	0.6	∞
Readout electronics	1.0	N	1	1	1.0	∞
Response time	0.0	R	√3	1	0.0	∞
Integration time	0.5	R	√3	1	0.3	∞
RF ambient conditions	0	R	√3	1	0	∞
Probe positioner mechanical tolerance	0.5	R	√3	1	0.3	∞
Probe positioning with respect to phantom shell	2.0	R	√3	1	1.2	∞
Extrapolation, interpolation, & integration algorithms for maximum SAR evaluation	5.0	R	√3	1	2.9	∞
Test Sample Related						
Device positioning	3	R	√3	1	1.7	11
Device holder uncertainty	3	R	√3	1	1.7	7
Output power variation – SAR drift measurement	5	R	√3	1	2.9	∞
Phantom and Tissue Parameters						
Phantom uncertainty – base thickness tolerance	10.0	R	√3	1	5.8	∞
Liquid conductivity – deviation from target values	0.4	R	√3	0.7	0.2	∞
Liquid conductivity – measurement uncertainty	1.5	R	√3	0.7	0.6	∞
Liquid permittivity – deviation from target values	0.8	R	√3	0.6	0.3	∞
Liquid permittivity – measurement uncertainty	3.5	R	√3	0.6	1.2	∞
Combined Standard Uncertainty		RSS			8.3	
Expanded Uncertainty (95% Confidence Level)					± 16.6	

APPENDIX F

COARSE SCANS FOR THE HIGHEST SAR REGION FOR THE CYBERTAN TECHNOLOGY WIRELESS LAN CARDBUS CARD MODEL WE701-I (FCC ID# N89-WE701I) WITH DELL MODEL PP01L HOST COMPUTER

February 13, 2004

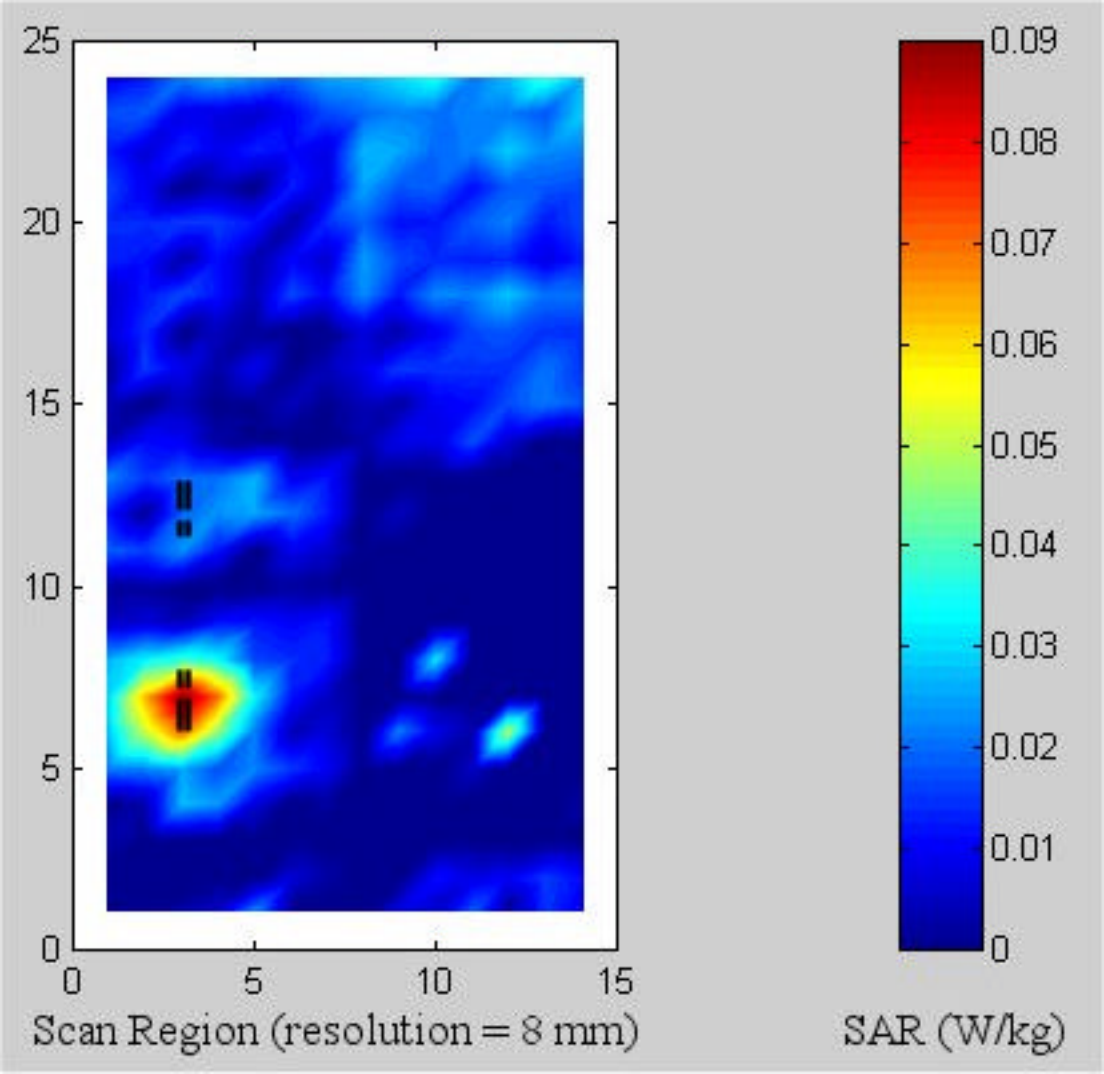


Fig. F.1. **Above-lap position (Configuration 1). Normal mode at 5.805 GHz.** Coarse scan for the highest SAR region for the Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host Computer.

Table F.1. **Above-lap position (Configuration 1). Normal mode at 5.805 GHz**. The SARs measured for the Cybertan Technology Wireless LAN Cardbus Card (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer.

1-g SAR = 0.102 W/kg **February 13, 2004**

a. At depth of 1 mm

0.194	0.287	0.294	0.300	0.227
0.125	0.228	0.283	0.280	0.231
0.201	0.341	0.369	0.281	0.246
0.299	0.330	0.315	0.328	0.210
0.187	0.175	0.229	0.194	0.246

b. At depth of 3 mm

0.086	0.124	0.125	0.124	0.104
0.091	0.107	0.135	0.134	0.116
0.111	0.133	0.135	0.116	0.125
0.131	0.132	0.122	0.134	0.114
0.086	0.108	0.117	0.111	0.153

c. At depth of 5 mm

0.053	0.058	0.049	0.052	0.050
0.064	0.057	0.065	0.061	0.055
0.066	0.041	0.047	0.050	0.065
0.058	0.056	0.048	0.058	0.064
0.051	0.070	0.064	0.074	0.116

d. At depth of 7 mm

0.049	0.040	0.025	0.034	0.034
0.043	0.038	0.041	0.034	0.031
0.046	0.015	0.028	0.031	0.040
0.035	0.036	0.033	0.038	0.040
0.044	0.052	0.043	0.063	0.103

e. At depth of 9 mm

0.047	0.037	0.023	0.033	0.032
0.026	0.028	0.035	0.031	0.027
0.037	0.020	0.028	0.027	0.033
0.030	0.032	0.037	0.034	0.029
0.043	0.043	0.034	0.061	0.097

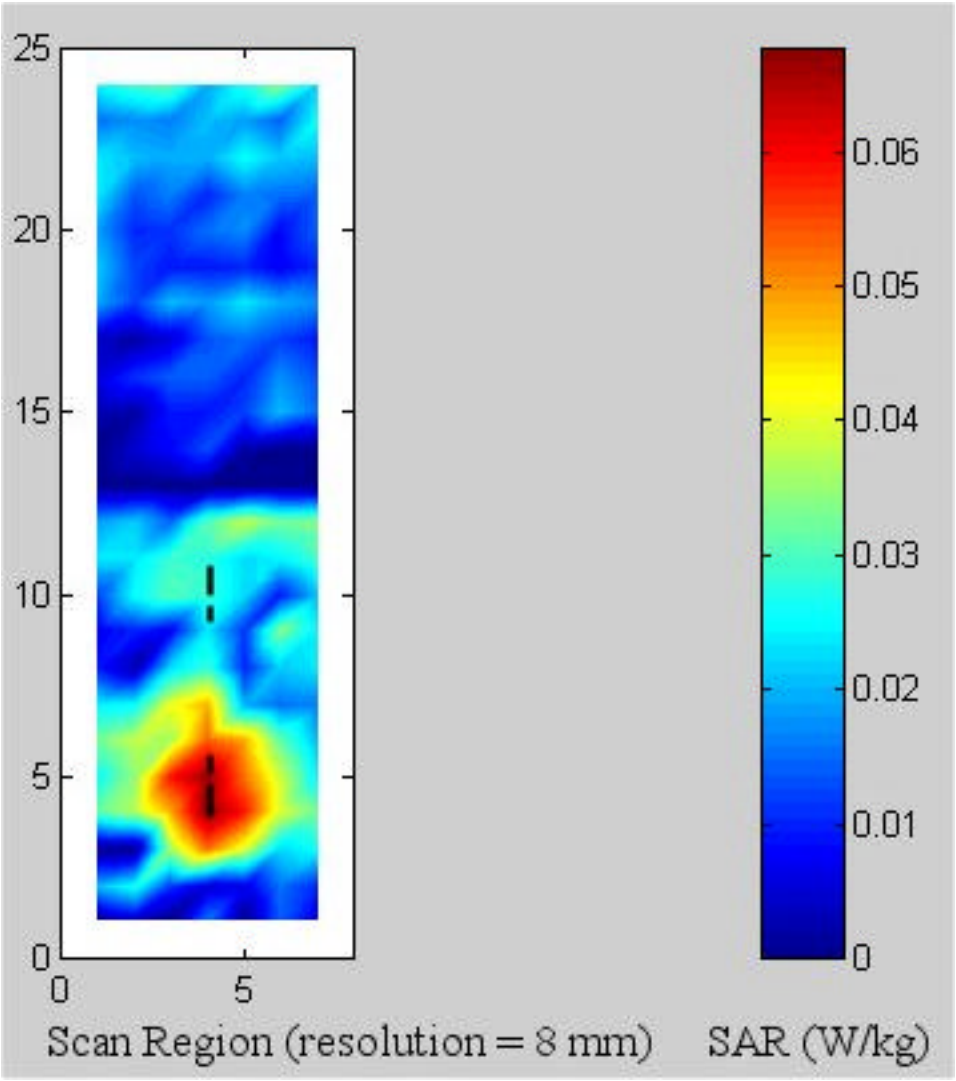


Fig. F.2. **Edge-on position (Configuration 2). Normal mode at 5.18 GHz.** Coarse scan for the highest SAR region for the Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host Computer.

Table F.2. **Edge-on position (Configuration 2). Normal mode at 5.18 GHz**. The SARs measured for the for the Cybertan Technology Wireless LAN Cardbus Card (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer.

1-g SAR = 0.076 W/kg **February 13, 2004**

a. At depth of 1 mm

0.128	0.149	0.138	0.133	0.109
0.132	0.177	0.150	0.159	0.102
0.132	0.158	0.233	0.180	0.122
0.140	0.156	0.180	0.152	0.156
0.111	0.124	0.169	0.156	0.117

b. At depth of 3 mm

0.079	0.091	0.085	0.081	0.080
0.083	0.090	0.083	0.092	0.076
0.080	0.084	0.106	0.095	0.080
0.094	0.085	0.097	0.082	0.084
0.079	0.081	0.091	0.091	0.083

c. At depth of 5 mm

0.056	0.064	0.062	0.056	0.058
0.059	0.051	0.055	0.060	0.059
0.056	0.059	0.058	0.057	0.058
0.068	0.057	0.065	0.056	0.058
0.057	0.055	0.057	0.063	0.062

d. At depth of 7 mm

0.046	0.052	0.053	0.046	0.042
0.049	0.038	0.046	0.047	0.048
0.047	0.053	0.046	0.043	0.046
0.055	0.049	0.055	0.049	0.052
0.044	0.041	0.044	0.053	0.051

e. At depth of 9 mm

0.041	0.046	0.048	0.041	0.034
0.045	0.034	0.043	0.042	0.040
0.046	0.050	0.042	0.037	0.038
0.050	0.045	0.049	0.046	0.047
0.038	0.035	0.038	0.047	0.048

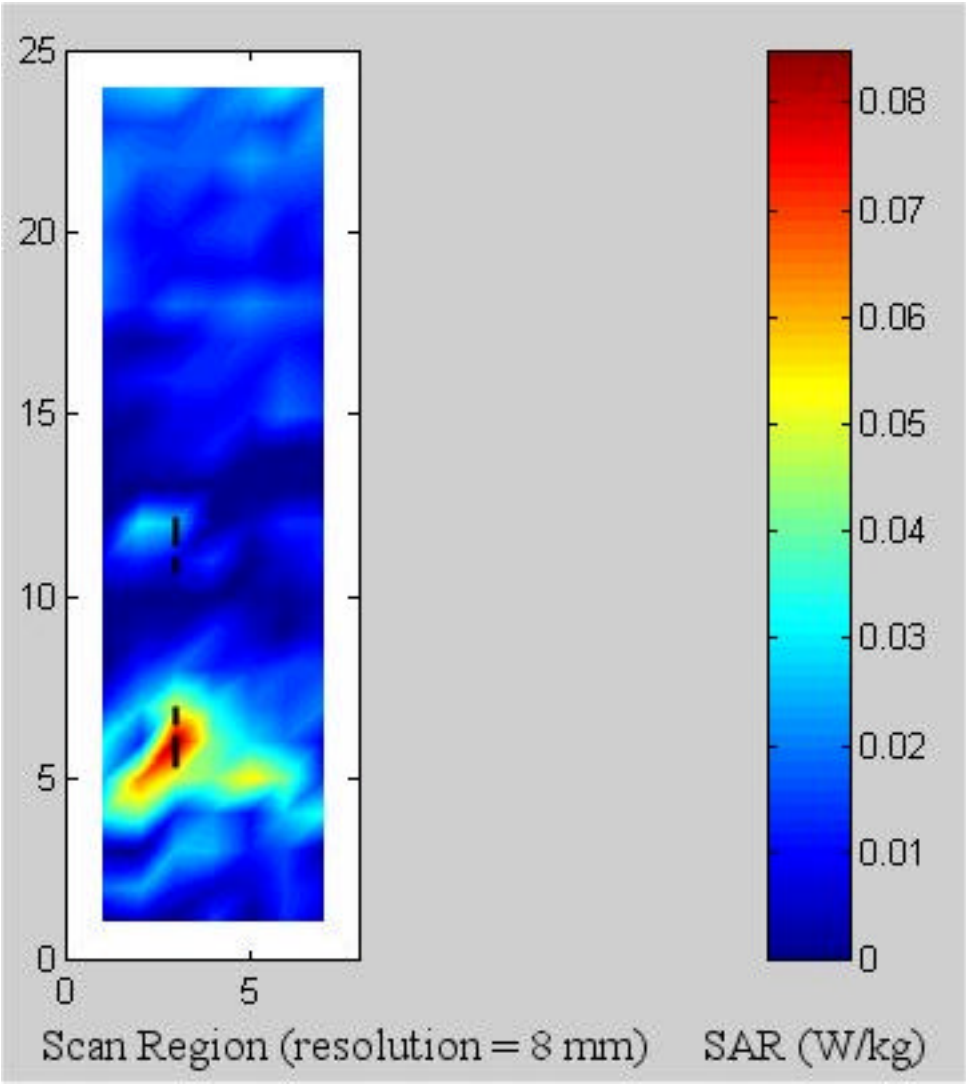


Fig. F.3. **Edge-on position (Configuration 2). Normal mode at 5.26 GHz.** Coarse scan for the highest SAR region for the Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host Computer.

Table F.3. **Edge-on position (Configuration 2). Normal mode at 5.26 GHz**. The SARs measured for the Cybertan Technology Wireless LAN Cardbus Card (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer.

1-g SAR = 0.078 W/kg **February 13, 2004**

a. At depth of 1 mm

0.131	0.101	0.135	0.106	0.146
0.143	0.101	0.193	0.127	0.102
0.087	0.182	0.231	0.202	0.165
0.127	0.145	0.182	0.162	0.101
0.102	0.169	0.149	0.179	0.098

b. At depth of 3 mm

0.077	0.071	0.089	0.077	0.094
0.090	0.084	0.098	0.072	0.079
0.094	0.103	0.122	0.115	0.118
0.083	0.088	0.100	0.088	0.072
0.083	0.103	0.089	0.096	0.074

c. At depth of 5 mm

0.053	0.059	0.065	0.057	0.064
0.065	0.063	0.058	0.051	0.063
0.080	0.067	0.071	0.076	0.090
0.063	0.062	0.062	0.057	0.053
0.066	0.071	0.060	0.056	0.056

d. At depth of 7 mm

0.045	0.054	0.053	0.044	0.049
0.052	0.046	0.045	0.044	0.053
0.060	0.055	0.053	0.063	0.072
0.053	0.050	0.047	0.047	0.042
0.054	0.056	0.048	0.042	0.044

e. At depth of 9 mm

0.042	0.049	0.046	0.038	0.044
0.044	0.038	0.039	0.039	0.045
0.046	0.051	0.047	0.058	0.057
0.046	0.042	0.040	0.041	0.037
0.046	0.048	0.043	0.036	0.037

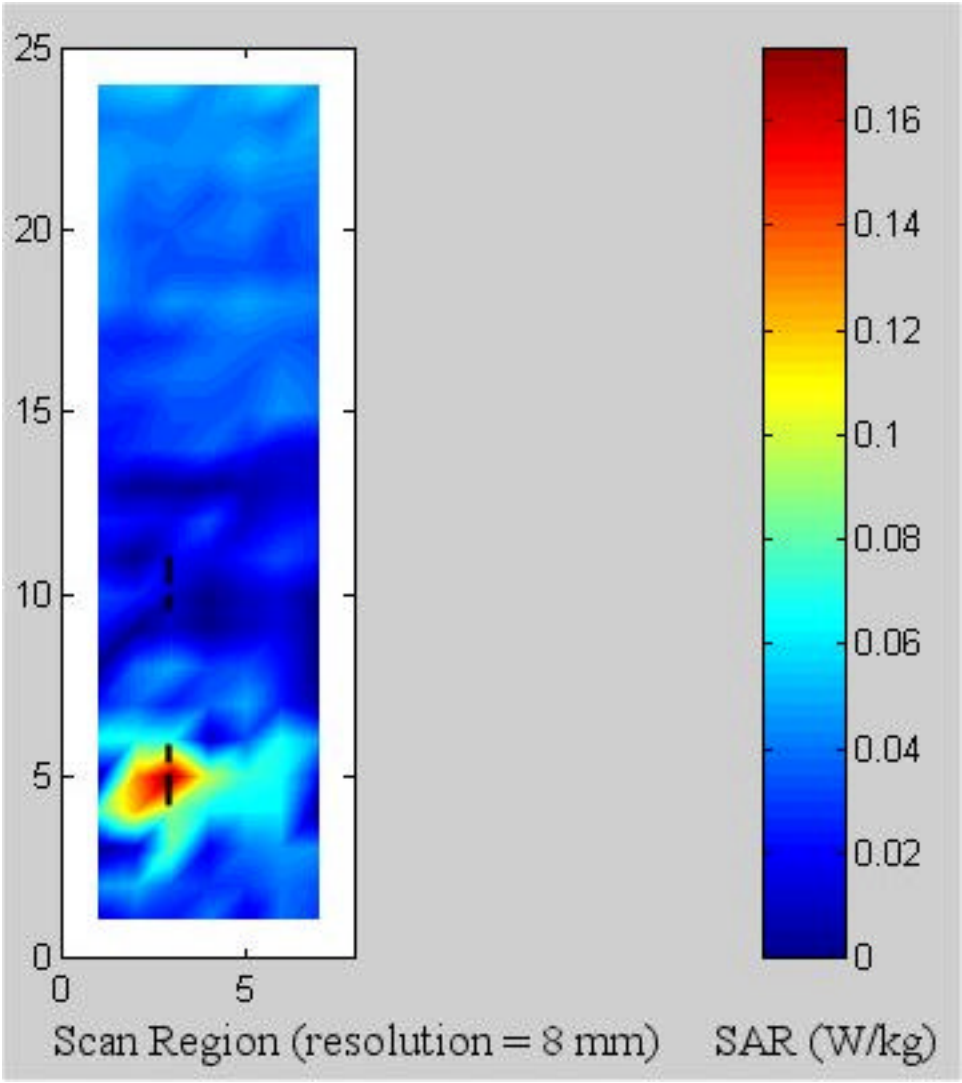


Fig. F.4. **Edge-on position (Configuration 2). Normal mode at 5.805 GHz.** Coarse scan for the highest SAR region for the Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host Computer.

Table F.4. **Edge-on position (Configuration 2). Normal mode at 5.805 GHz**. The SARs measured for the Cybertan Technology Wireless LAN Cardbus Card (FCC ID# N89-WE701I) inserted into Dell Model PP01L Host Computer.

1-g SAR = 0.125 W/kg **February 13, 2004**

a. At depth of 1 mm

0.202	0.183	0.193	0.201	0.201
0.247	0.231	0.294	0.231	0.239
0.232	0.324	0.391	0.333	0.209
0.226	0.249	0.253	0.223	0.196
0.172	0.170	0.201	0.174	0.162

b. At depth of 3 mm

0.127	0.131	0.120	0.113	0.135
0.145	0.139	0.151	0.132	0.139
0.129	0.158	0.215	0.189	0.144
0.153	0.174	0.148	0.141	0.138
0.136	0.122	0.156	0.141	0.145

c. At depth of 5 mm

0.092	0.097	0.086	0.076	0.102
0.088	0.092	0.085	0.091	0.095
0.088	0.095	0.126	0.119	0.111
0.111	0.118	0.102	0.101	0.098
0.103	0.090	0.115	0.121	0.129

d. At depth of 7 mm

0.078	0.077	0.072	0.065	0.086
0.061	0.072	0.063	0.078	0.081
0.076	0.081	0.089	0.091	0.092
0.088	0.082	0.085	0.084	0.073
0.080	0.072	0.085	0.102	0.110

e. At depth of 9 mm

0.071	0.066	0.066	0.060	0.076
0.052	0.067	0.058	0.074	0.077
0.072	0.081	0.076	0.081	0.076
0.075	0.065	0.075	0.078	0.060
0.067	0.062	0.068	0.081	0.087

APPENDIX G

VARIATION OF SAR AS A FUNCTION OF DEPTH Z IN THE LIQUID FOR LOCATIONS OF THE HIGHEST SAR (FROM TABLES F.1 TO F.4)

February 13, 2004

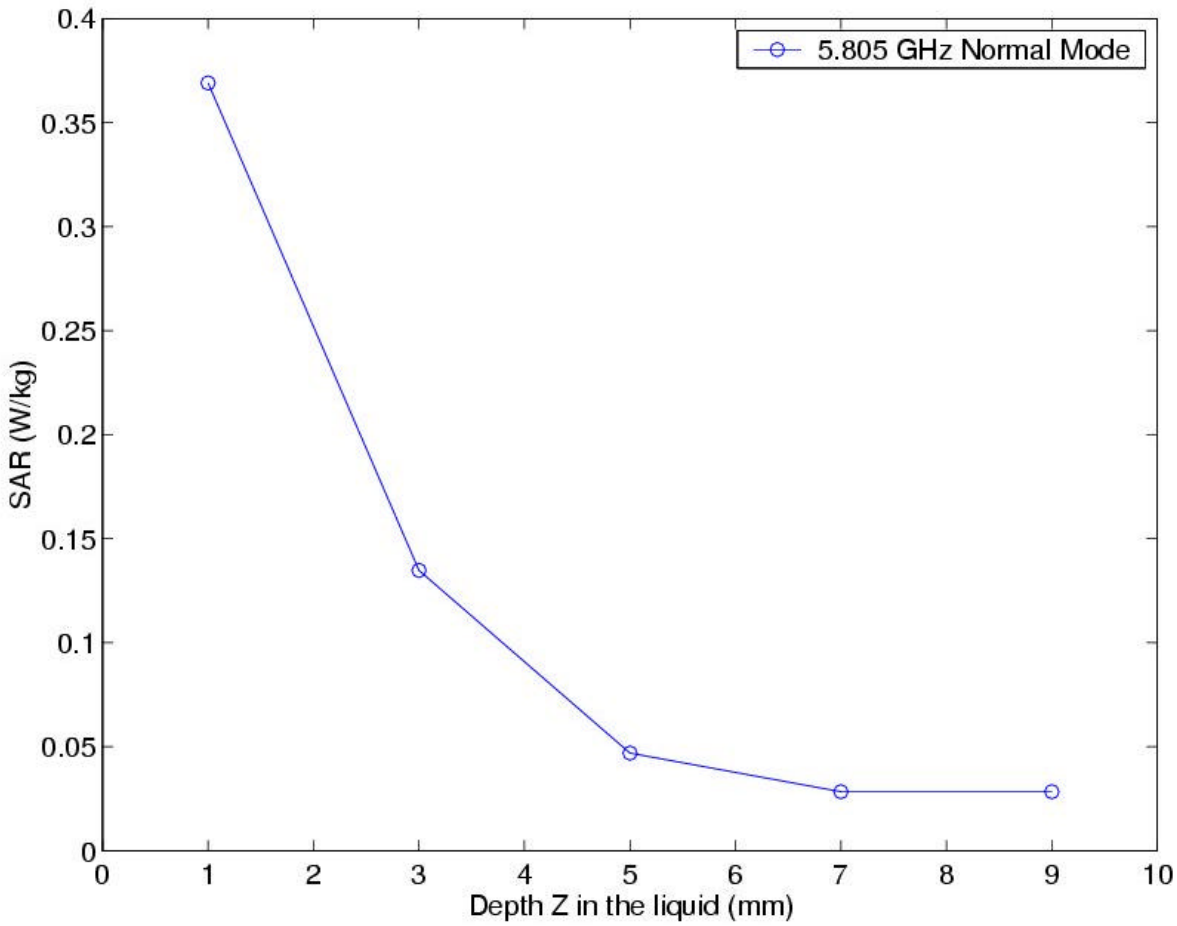


Fig. G.1. **Above-lap, Configuration 1.** Plot of the SAR variation as a function of depth Z in the liquid for locations of the highest SAR for the **normal** mode of Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host (from Table F.1).

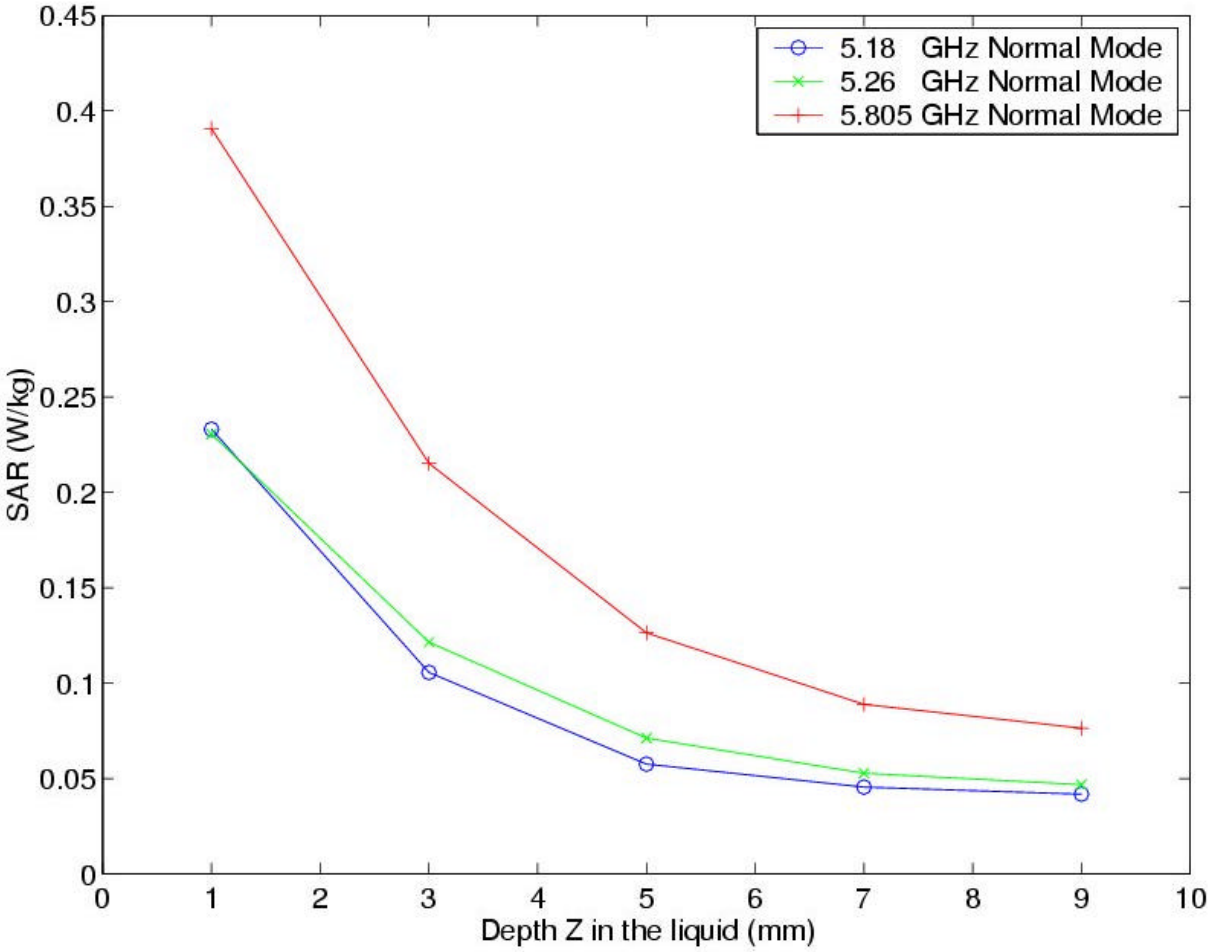


Fig. G.2. **Edge-on, Configuration 2.** Plot of the SAR variation as a function of depth Z in the liquid for locations of the highest SAR for the **normal** mode of Cybertan Technology Wireless LAN Cardbus Card inserted into Dell Model PP01L Host Computer (from Tables F.2 to F.4).