ABSTRACT

This report presents the experimental results and the modeling of the radiation from power bus structures in printed circuit boards, which is part of the EMC Export System project. The test boards, test setup and test procedure are described in detail. All experimental results (plots) are included without drawing general conclusions.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ivii</td>
</tr>
<tr>
<td>SECTIONS</td>
<td></td>
</tr>
<tr>
<td>1. TEST BOARDS</td>
<td>1</td>
</tr>
<tr>
<td>2. POWER BUS RADIATION MEASUREMENTS</td>
<td>5</td>
</tr>
<tr>
<td>3. AN ALGORITHM TO ESTIMATE POWER BUS RADIATION</td>
<td>22</td>
</tr>
<tr>
<td>3.1. Maximum Transient Current and Its Spectrum</td>
<td>23</td>
</tr>
<tr>
<td>3.2. Power Bus Impedance</td>
<td>36</td>
</tr>
<tr>
<td>3.3. Quality Factor and Radiation Efficiency</td>
<td>47</td>
</tr>
<tr>
<td>4. COMPARISON OF ESTIMATED AND MEASURED RADIATION</td>
<td>55</td>
</tr>
<tr>
<td>5. OTHER</td>
<td>S11 AND RADIATION</td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>A. Test Procedure for Measuring Radiation Using Tektronix 2712 Spectrum Analyzer</td>
<td>73</td>
</tr>
<tr>
<td>B. Test Procedure for Measuring Time-Domain Waveform Using Tektronix TDS 520A Digitizing Oscilloscope</td>
<td>75</td>
</tr>
<tr>
<td>C. Test Procedure for Measuring Voltage/Current Spectrum Using Tektronix 2712 Spectrum Analyzer</td>
<td>77</td>
</tr>
<tr>
<td>D. Test Procedure for Measuring Input Impedance Using HP4291A HF Impedance/Material Analyzer</td>
<td>79</td>
</tr>
<tr>
<td>E. Matlab Program to Calculate Board Impedance and Effective Capacitance from Measured Voltage/Current Spectrum</td>
<td>81</td>
</tr>
<tr>
<td>F. Test Procedure for Measuring S Parameters Using HP8753D Network Analyzer</td>
<td>85</td>
</tr>
<tr>
<td>G. Test Procedure for Measuring Radiation</td>
<td>S21</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>89</td>
</tr>
</tbody>
</table>
### LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1. Board 6 Layout</td>
<td>2</td>
</tr>
<tr>
<td>Figure 1.2. Board 7 Layout</td>
<td>2</td>
</tr>
<tr>
<td>Figure 1.3. A Photo of Boards 6 and 7</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1.4. Layout of Boards 1 and 2</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1.5. Mock-Up Board Layout</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2.1. Experimental Setup for Radiation Measurements</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2.2. Measuring Radiation Inside the Shielding Room</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.3. Radiation of Board 6 for 10 Configurations</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.4. Radiation of Board 6 Without Decoupling Capacitors for 8 Configurations</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2.5. Capacitively Short the Two Shorter Edges of Board 6</td>
<td>13</td>
</tr>
<tr>
<td>Figure 2.6. Radiation of Board 6 With Two Short Edges Capacitively Shorted</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.7. Radiation of Board 6 With All Edges Capacitively Shorted</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.8. Board 6 With an Extra Return Plane</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.9. Radiation of Board 6 With Extra Return Plane</td>
<td>21</td>
</tr>
<tr>
<td>Figure 3.1. A Triangular Approximation of Transient Current</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.2. Calculated Current Spectrum</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.3. Noise Current Being Measured Using Tek TDS520A Digitizing Oscilloscope</td>
<td>25</td>
</tr>
<tr>
<td>Figure 3.4. Clock Signal Being Measured Using Tek TDS520A Digitizing Oscilloscope</td>
<td>26</td>
</tr>
<tr>
<td>Figure 3.5. Current Waveform Measured at Connector 1</td>
<td>26</td>
</tr>
<tr>
<td>Figure 3.6. One Period of Current Waveform</td>
<td>27</td>
</tr>
<tr>
<td>Figure 3.7. Voltage/Current Spectrum Being Measured Using Tek 2712 Spectrum Analyzer</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.8. Measured and Calculated Spectrum at Connector 1</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.9. Actual Waveform and Triangle-Shaped Approximation</td>
<td>29</td>
</tr>
<tr>
<td>Figure 3.10. Triangle-Shaped Approximation and Gaussian Approximation</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 3.11. Current Spectrum Estimations Using Triangle Waveform With Different Current Peak Values or Rise/Fall Time

Figure 3.12. Voltage Waveform Measured at Connector 2

Figure 3.13. Voltage Spectrum Measured at Connector 2

Figure 3.14. Voltage Waveform Measured at Connector 3

Figure 3.15. Voltage Spectrum Measured at Connector 3

Figure 3.16. Measuring Impedance Using HP4291A RF Impedance/Material Analyzer

Figure 3.17. A Close-Up of the Connections Between Test Station and Test Board

Figure 3.18. Impedance of Board 1 at C2D5 in Region 1

Figure 3.19. Impedance of Board 1 at C6G3 in Region 2

Figure 3.20. Impedance of LG Board on 5VST Plane

Figure 3.21. Impedance of LG Board on 5VDD Plane

Figure 3.22. Impedance of Board 2 at C2D5 in Region 1

Figure 3.23. Impedance of Board 2 at C6G3 in Region 2

Figure 3.24. Impedance of Board 3 at L1

Figure 3.25. Impedance of Board 3 at L2

Figure 3.26. Impedance of Board 3 at L3

Figure 3.27. Impedance of Board 6 at Connector 2

Figure 3.28. Impedance of Board 6 at Connector 3

Figure 3.29. Impedance Spectrum of Board 6 With 1 MHz Oscillator

Figure 3.30. Impedance Spectrum of Board 6 With 10 MHz Oscillator

Figure 3.31. $|S_{11}|$ of Board 7 at a Corner Connector

Figure 3.32. $|S_{11}|$ of Board 7 at Center Connector

Figure 3.33. $|S_{11}|$ of Board 7 With Different Configurations

Figure 3.34. The Variation of Permittivity as a Function of Frequency

Figure 3.35. $|S_{11}|$ of Board 7 at Corner Connector With Edges Open

Figure 3.36. $|S_{11}|$ of Board 7 at Center Connector With Edges Open

Figure 3.37. $|S_{11}|$ of Board 7 at Corner Connector With Edges Sealed

Figure 3.38. $|S_{11}|$ of Board 7 at Center Connector With Edges Sealed

Figure 3.39. Comparison of Quality Factors for Boards With Different Thickness

Figure 3.40. $|S_{11}|$ of the Board 6
Figure 3.41. $|S_{11}|$ of Board 1 ........................................................................................................ 54
Figure 4.1. Comparison of Measured and Calculated Radiation ........................................ 56
Figure 5.1. Test Setup for Measuring $|S_{11}|$ and Radiation $|S_{21}|$ .............................................. 57
Figure 5.2. Radiation $|S_{21}|$ Being Measured Inside the Shielding Room ......................... 58
Figure 5.3. Test Setup Outside the Shielding Room ............................................................. 58
Figure 5.4. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 7 at Corner Connector .............................. 60
Figure 5.5. $|S_{11}|$ and Radiation $|S_{21}|$ of 3-Layer Board 7 .................................................. 63
Figure 5.6. The Point Connections on 3-Layer Board 7 ...................................................... 63
Figure 5.7. $|S_{11}|$ or Radiation $|S_{21}|$ of 3-Layer Board 7 With Different Connections ...... 67
Figure 5.8. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 1 ................................................................. 70
Figure 5.9. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 2 ................................................................. 72
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1. Calculated and Measured Radiation Using Calculated Current Spectrum</td>
<td>55</td>
</tr>
<tr>
<td>4.2. Calculated and Measured Radiation Using Measured Current Spectrum</td>
<td>56</td>
</tr>
</tbody>
</table>
1. Test Boards

A two-sided 45-mil thick test board of dimensions 8 x 3.2 inches was built especially for this study. This board is referred to as Board 6 in this report. An unpopulated version of Board 6, Board 7, was also built.

The layout of Board 6 is shown in Figure 1.1. This board was powered by three 1.5-volt batteries. A small slide switch connecting to the batteries and the power plane was used to turn the power on or off. The DUT was an IDT74FT807BT clock driver. A 10-MHz oscillator was employed to produce the input to the clock driver. The $V_{CC}$ pin of the clock driver was connected to the power plane through three 10-ohm resistors in parallel. In addition, four 1-nF decoupling capacitors were mounted between the power and return planes along the left end of the board.

SMA connectors were attached to the board at positions 1, 2, and 3 as shown in Figure 1.1. The shield of Connector 1 was connected to the return plane, while the center conductor was connected to the $V_{CC}$ pin of the clock driver. Because the $V_{CC}$ pin of the clock driver was connected to the power plane through three 10-ohm resistors in parallel, Connector 1 can be used to monitor the noise current, $I_{CC}$, times the equivalent 3.3-ohm resistance. Connectors 2 and 3 were connected to the power and return planes and used to measure the power bus voltages close-to and far-from the clock driver, respectively.

The layout of Board 7 is shown in Figure 1.2. It was an unpopulated version of Board 6. Three SMA connectors were mounted on it. Two connectors were near the corner. The other connector was at the center of the board. Figure 1.3 shows a photo of Boards 6 and 7.

In addition to Boards 6 and 7, three other boards were employed for this study. Board 1 was a 4-layer personal computer motherboard provided by a chip manufacturer. It was fully populated with a large number of components. Figure 1.4 shows the geometry of this board. The power plane was divided into two power islands, Region 1 and Region 2. The bonding pads of the decoupling capacitors used in the experiments are also labeled in Figure 1.4.
Figure 1.1. Board 6 Layout

Figure 1.2. Board 7 Layout
Board 2 was an unpopulated version of Board 1. Board 3 was a mock-up of Board 2. As shown in Figure 1.5, the 2-layer mock up board has the same width and length as Board 2. The shapes of the power islands are also similar, but the spacing
between the power and return layers is about 50 mils instead of 40 mils for the motherboard. There is a 100-mil gap between Region 1 and Region 2. Three short 85-mil diameter semi-rigid probes were attached between power and return planes at locations L1, L2, and L3 to make the S-parameter measurements.

Figure 1.5. Mock-Up Board Layout
2. Power Bus Radiation Measurements

The radiated fields from the test board were measured inside a shielded room. The test setup is illustrated in Figure 2.1. An EMCO BiConiLog 3142 antenna and a Tektronix 2712 spectrum analyzer were used to receive the signal. Figure 2.2 shows the experiment setup inside the shielded room. The test procedure is described in Appendix A in detail.

The orientations of the antenna and the test board were adjusted to make different measurements. The horizontally positioned antenna was used to measure horizontal electric field or vertical magnetic field. The vertically positioned antenna was used to measure vertical electric field or horizontal magnetic field. In addition, the test board can be positioned in up to six different orientations. Figure 2.3 shows the radiation measurements for ten different configurations. The orientations of the antenna and the test board are illustrated beside each plot.

Figure 2.1. Experimental Setup for Radiation Measurements
Figure 2.2. Measuring Radiation Inside the Shielded Room
Figure 2.3. Radiation from Board 6 in 10 Configurations
To investigate the effect of decoupling capacitors, experiments were made on Board 6 without the decoupling capacitors as shown in Figure 2.4. As expected, the radiation levels are higher on the board without capacitors.
Figure 2.4. Radiation from Board 6 without Decoupling Capacitors for 8 Configurations
To investigate the contribution of the fringing electric field on power bus radiation from Board 6 without decoupling capacitors, the two shorter edges of Board 6 were capacitively shorted using copper tape as shown in Figure 2.5. This was to shield the vertical fringing electric field on the two shorter edges. The radiation measurement for the shorted board is shown in Figure 2.6.

Figure 2.5. Capacitively Short the Two Shorter Edges of Board 6
Figure 2.6. Radiation from Board 6 with the Two Short Edges Capacitively Shorted

All edges of Board 6 were then capacitively shorted and the radiation measurements are shown in Figure 2.7. The major contributor to the radiation is now the magnetic fields induced by currents on the surface of planes.
Figure 2.7. Radiation from Board 6 with All Edges Capacitively Shorted
To investigate the effect of EMI shielding provided by a symmetric power bus structure, another layer of copper tape was added above the power plane of Board 6 without decoupling capacitors (See Figure 2.8). The added return plane was connected to the original return plane at the four corners. Figure 2.9 shows the measured radiation on this 3-layer board for eight configurations. Compared to Figure 2.4, the overall peak radiation levels are reduced by 10-15 dB.

Figure 2.8. Board 6 with an Extra Return Plane
Figure 2.9. Radiation from Board 6 with an Extra Return Plane
3. An Algorithm to Estimate Power Bus Radiation

A procedure to estimate power bus radiation is outlined below. Some of the parameters are examined later in this section.

1. Estimate the periodic and maximum transient current ($I_p$) drawn by each IC and calculate the current spectrum ($I_{CC}$) using the time domain information. This step will be discussed in detail in Section 3.1.

2. Estimate the power bus impedance ($Z_B$). This will provide an approximation of the variation of power bus impedance with frequency. This step will be examined in Section 3.2.

3. Calculate the spectrum of the available power ($P_{AVAIL}$) in the power bus structure using,

$$P_{AVAIL} = (I_{CC})^2 \text{Re}(Z_B)$$  \hspace{1cm} (1)

4. Estimate the power radiated from the power bus structure ($P_{RAD}$). This is determined by the radiation efficiency K.

$$P_{RAD} = KP_{AVAIL}$$  \hspace{1cm} (2)

The K parameter will be justified in Section 3.3.

5. Using $P_{RAD}$, calculate the power density incident to the antenna ($W_{INC}$).

$$W_{INC} = P_{RAD} / (2\pi r^2)$$  \hspace{1cm} (3)

where $r$ is the distance from the test board to antenna. The radiated electric field is calculated assuming isotropic radiation into a hemisphere, accounting for the ground plane present in the far field measurements. Then, calculate the electric field received by the antenna ($E_{REC}$),

$$E_{REC} = \sqrt{W_{INC} \eta_0}$$  \hspace{1cm} (4)

where $\eta_0$ is the characteristic impedance in free space.

6. Using the antenna factor (AF), calculate the induced voltage across the antenna terminals ($V_{REC}$) and the power received by the network analyzer ($P_{RECdBm}$). Compare the results with the measured radiation at resonant peaks.

$$V_{REC} = E_{REC} / AF$$  \hspace{1cm} (5)
\[ P_{REC_{dBm}} = 30 + 10 \log_{10}(V_{REC}^2 / R_L) \]  

where \( V_{REC} \) is the induced voltage in the antenna terminals, and \( R_L \) is the load impedance of the network analyzer.

### 3.1. Maximum Transient Current and Its Spectrum

The first step of the algorithm is to estimate the maximum peak current drawn by integrated circuits in the board and the current spectrum. Only the clock driver is considered in this step.

If \( C_{PD} \) is given in the data sheet, the peak current, \( I_p \), can be calculated as,

\[ I_p = C_{PD} V_C / \Delta t \]  

where \( V_C \) is the DC power bus voltage, \( \Delta t \) is the switching time of the IC device and is equal to the sum of the rise and fall times.

If \( I_{CCD} \) is given, \( C_{PD} \) can be calculated from the \( I_{CCD} \) value using,

\[ C_{PD} = I_{CCD} / V_C \]  

As a result, \( I_p \) can be obtained using,

\[ I_p = I_{CCD} / \Delta t \]  

For the clock driver used in the test board, the typical \( I_{CCD} \) value is 0.4 mA/MHz. The output rise and fall times are 1.5 ns, so the switching time, \( \Delta t \), is 3 ns. The estimated maximum peak transient current, \( I_p \), is 133 mA.

The transient current can be approximated to have a triangle-shaped waveform, as illustrated in Figure 3.1. Matlab\textsuperscript{®} programs were developed to calculate the current spectrum from the time domain waveform. From the data sheet, the rise and fall times are 1.5 ns. The clock period, \( T \), is 100 ns. The estimated peak transient current, \( I_{p1} \) and \( I_{p2} \), is 133 mA. Using these parameters, the current spectrum was calculated and shown in Figure 3.2.

In Figure 3.2, the upper plot shows the calculated current amplitude at each harmonic. The lower plot shows the calculated power spectrum received by a spectrum analyzer using,

\[ P(n) = 10 \times \log_{10} \left[ \frac{(I_{CC}(n) \times 3.3)^2}{R \times 0.001} \right] \]  

where \( R \) is the load impedance, \( I_{CC}(n) \) is the current amplitude at the \( n \)-th harmonic.
where $P(n)$ is the power amplitude at the $n^{th}$ harmonic; $I_{CC}(n)$ is the current amplitude at the $n^{th}$ harmonic; $R$ is the load impedance (50 ohms) of the spectrum analyzer; 3.3 is the equivalent resistance connected to the $V_{CC}$ pin of the clock driver; 0.001 is a factor to convert dBW to dBm.

![Figure 3.1. A Triangular Approximation of Transient Current](image1)

![Figure 3.2. Calculated Current Spectrum](image2)
In order to validate the formulas to calculate peak transient current, the current drawn by the clock driver on Board 6 was measured. The measurement was made using a Tektronix TDS520A digitizing oscilloscope. The transient current was measured as shown in Figure 3.3. The scope input was connected to Connector 1, which was very close to the $V_{CC}$ pin of the clock driver. The clock signal was measured as shown in Figure 3.4. Appendix B describes the measurement procedure in detail.

Figure 3.5 shows the measured noise current and clock signal. The measured voltage waveform shown in the lower plot is the current waveform times the 3.3-ohm equivalent resistance.

Figure 3.6 shows a one-period expansion of the current waveform. From these two figures, the maximum current peak is about 150 mA, the rise and fall times for each current peak are 2.5 ns, and the period of the waveform is 100 ns.
Figure 3.4. Clock Signal Being Measured Using Tek TDS520A Digitizing Oscilloscope

Figure 3.5. Current Waveform Measured at Connector 1
The current spectrum was measured using a Tektronix 2712 spectrum analyzer. The input of the spectrum analyzer was connected to Connector 1 through a DC block. Figure 3.7 shows a spectrum measurement being made using the spectrum analyzer. The test procedure is described in Appendix C.

The measured spectrum is compared with the calculated spectrum in Figure 3.8. At resonant frequencies, the calculated spectrum is 10-11 dB higher than the measured spectrum. Figure 3.9 compares the measured waveform with the triangle-shaped approximation. Note that the actual waveform is much smoother than the approximation.
Figure 3.7. Voltage/Current Spectrum Being Measured Using Tek 2712 Spectrum Analyzer

Figure 3.8. Measured and Calculated Spectrum at Connector 1
Two methods were investigated to obtain a better spectrum estimation. First, the shape of the current waveform was modified. A Gaussian waveform was adopted and is compared with the triangle-shaped waveform in Figure 3.10. In the spectra calculation, the actual rise and fall times of 2.5 ns were used. Second, the original triangle approximation was used, but the peak current value and switching times were adjusted. Figure 3.11 illustrates the effect of varying the current peak value and rise/fall time of the triangular waveform. The data used to calculate the spectrum are shown in the title of each plot. The last plot, corresponding to the case of doubling the rise/fall time and halving the current peak value, gives optimum result. The estimated spectrum is only 4 dB higher than the measured value for the first resonance, and equal to the measured spectrum for the second and third resonances.
Figure 3.10. Triangle-Shaped Approximation and Gaussian Approximation
Figure 3.11. Current Spectrum Estimations Using Triangle Waveform with Different Current Peak Values or Rise/Fall Time

In addition to the current measurements, power bus voltage waveforms and spectra were also measured at Connectors 2 and 3.

Connector 2 is located close to the clock driver. The voltage waveform measured at this point is shown in Figure 3.12 and the voltage spectrum is shown in Figure 3.13.

Connector 3 is located at the other end of the board and is distant from the circuit. The voltage waveform measured at this point is shown in Figure 3.14 and the voltage spectrum is illustrated in Figure 3.15.
Figure 3.12. Voltage Waveform Measured at Connector 2

Figure 3.13. Voltage Spectrum Measured at Connector 2
Figure 3.14. Voltage Waveform Measured at Connector 3

Figure 3.15. Voltage Spectrum Measured at Connector 3
3.2. **Power Bus Impedance**

The second step of the power bus radiation algorithm is to estimate the power bus impedance as a function of frequency. The power bus impedance can be set to the characteristic impedance of the power bus geometry for populated boards. For Board 6, the calculated characteristic impedance is about 2.5 ohms.

Impedance measurements were made on several unpopulated and populated circuit boards, including Boards 1, 2, 3, and 6. An HP4291A RF impedance/material analyzer with a low impedance test head was used to make the impedance measurements. Semi-rigid probes or SMT connectors were attached to the power and return planes at the desired port locations. The impedance analyzer was connected to the probe or the connector through a low-loss precision cable. An open-short-load calibration, port extension, and fixture compensation were performed to move the measurement plane to the power bus structure. The test procedure is described in Appendix D in detail. Figure 3.16 shows an impedance measurement being made using the impedance analyzer. Figure 3.17 provides a close look at the connections between the test station and the board.

![Figure 3.16. Measuring Impedance using the HP4291A RF Impedance/Material Analyzer](image)
Figure 3.17. A Close-Up of the Connections between Test Station and Test Board

Figure 3.18 and Figure 3.19 show the input impedance in Regions 1 and 2 of Board 1. The impedance curves are relatively low and smooth.

Figure 3.20 and Figure 3.21 show the impedance of another populated board. The spikes at around 300 MHz may be due to resonances between the board capacitance and probe inductance. At other frequencies the impedance is below 10 ohms.

Figure 3.22 and Figure 3.23 show the input impedance of Board 2 in Regions 1 and 2.

Figure 3.24, Figure 3.25, and Figure 3.26 show the input impedance of Board 3 at locations L1, L2, and L3. The spikes in the impedance curve are sharp because this is an unpopulated board.

Figure 3.27 and Figure 3.28 show the impedance of Board 6 measured through Connectors 2 and 3. The difference of the two impedance curves at 190 MHz is due to the decoupling capacitors mounted near Connector 2 (See Figure 1.1).
Figure 3.18. Impedance of Board 1 at C2D5 in Region 1

Figure 3.19. Impedance of Board 1 at C6G3 in Region 2
Figure 3.20. Impedance of LG Board on 5VST Plane

Figure 3.21. Impedance of LG Board on 5VDD Plane
Figure 3.22. Impedance of Board 2 at C2D5 in Region 1

Figure 3.23. Impedance of Board 2 at C6G3 in Region 2
Figure 3.24. Impedance of Board 3 at L1

Figure 3.25. Impedance of Board 3 at L2
Figure 3.26. Impedance of Board 3 at L3

Figure 3.27. Impedance of Board 6 at Connector 2
The board impedance as a function of frequency (impedance spectrum) can also be evaluated by dividing the voltage spectrum by the current spectrum. Figure 3.29 shows the results of some experiments done on Board 6 with a 1-MHz oscillator. There are three figures: the first figure has a frequency range of 0-100 MHz; the second figure has a range of 0-200 MHz; the third figure has a range of 0-1 GHz, and individual harmonics are not visible. Four plots are contained in each figure. The first plot is the current spectrum measured at Connector 1 on Board 6. The second plot is the voltage spectrum measured at Connector 2 on Board 6. Only the peak value of each harmonic is used (See the red dots in the first two plots). The third plot is the impedance spectrum calculated by,

\[
Z(nf_0) = R_L \times 10^{\frac{V_{CCdBm} - I_{CCdBm}}{20}}
\]

where \(n\) is the harmonic index; \(f_0\) is the fundamental frequency; \(R_L\) is the 50-ohm load impedance; \(V_{CCdBm}\) is the amplitude of harmonics in the voltage spectrum; \(I_{CCdBm}\) is the amplitude of harmonics in the current spectrum. The last plot is an estimation of effective capacitance of the board calculated from,
\[ |C(nf_0)| = \frac{1}{2\pi nf_0 |Z(nf_0)|}. \] (12)

From the figure, the board impedance ranges from 0 to 2 ohms, which is consistent with the calculated characteristic impedance of 2.5 ohms. The Matlab program used to produce these plots is provided in Appendix E.
Figure 3.29. Impedance Spectrum of Board 6 With 1 MHz Oscillator
Figure 3.30 shows the results of similar experiments on Board 6 with a 10-MHz oscillator. There are two figures: one has a frequency range of 0-1 GHz; the other has a range of 0-1.8 GHz, which reaches the frequency limit of the Tek 2712 spectrum analyzer. The four plots in each figure are similar to those in Figure 3.29.
3.3. **Quality Factor and Radiation Efficiency**

The radiated power is determined by the radiation efficiency, $K$. The $K$ parameter can be expressed in terms of quality factors as

$$K = \frac{1}{Q_{RAD}} = \frac{Q_T}{Q_{RAD}}$$  \hspace{1cm} (13)

where $Q_T$ is the total quality factor for a circuit board. $Q_{RAD}$ is the quality factor due to radiation losses.

The radiation quality factor, $Q_{RAD}$, can be evaluated using $|S_{11}|$ measurements on unpopulated boards. The total quality factor, $Q_T$, can be evaluated using $|S_{11}|$ measurements on populated boards. Appendix F describes the test procedure for measuring S parameters in detail.

![Impedance Spectrum of Board 6 with a 10 MHz Oscillator](image)

Figure 3.30. Impedance Spectrum of Board 6 with a 10 MHz Oscillator
$|S_{11}|$ measurements were made on Board 7 at a corner connector as shown in Figure 3.31. The quality factors estimated for each peak are labeled in the figure. Figure 3.32 shows the $|S_{11}|$ and quality factor of Board 7 at the center connector.

Figure 3.33 compares the $|S_{11}|$ data of Board 7 with edges open or sealed, at corner or center connectors.

Figure 3.31. $|S_{11}|$ of Board 7 at a Corner Connector
Figure 3.32. $|S_{11}|$ of Board 7 at Center Connector

Figure 3.33. $|S_{11}|$ of Board 7 with Different Configurations
Figure 3.34 uses the resonant frequencies to calculate the relative permittivity at resonant points. The permittivity decreases as the frequency increases.

Figure 3.35, Figure 3.36, Figure 3.37, and Figure 3.38 show the measured $|S_{11}|$ of Board 7 at corner or center connectors, with edges open or sealed. The frequency range was extended to 4.0 GHz to observe higher frequency resonances.

Figure 3.39 compares the quality factors of boards with different thicknesses. Other dimensions of the boards were the same. The resonant frequencies are slightly different. The quality factor for the thinner board is obviously larger than that for the thicker board.

![Figure 3.34. The Variation of Permittivity as a Function of Frequency](image)
Figure 3.35. $|S_{11}|$ of Board 7 at Corner Connector with Edges Open

Figure 3.36. $|S_{11}|$ of Board 7 at Center Connector with Edges Open
Figure 3.37. $|S_{11}|$ of Board 7 at Corner Connector with Edges Sealed

Figure 3.38. $|S_{11}|$ of Board 7 at Center Connector with Edges Sealed
Figure 3.39. Comparison of Quality Factors for Boards with Different Thickness

Figure 3.40 shows the $|S_{11}|$ data of Board 6 at Connectors 2 (upper plot) and 3 (lower plot). The plots presented above are all for unpopulated boards. Figure 3.41 shows the measured $|S_{11}|$ of Board 1, a fully populated computer motherboard. The curve is very smooth and the quality factor should be very low.
Figure 3.40. $|S_{11}|$ of the Board 6

Figure 3.41. $|S_{11}|$ of Board 1
4. Comparison of Estimated and Measured Radiation

The calculated and measured radiation levels at resonance are compared in Table 4.1. The differences between the measured radiation and calculated radiation are 15 dB for the first two resonances and 18 dB for the third resonance. This is primarily due to the error in the estimation of the current spectrum. As shown in Figure 3.8, the calculated current spectrum is 10-11 dB higher than the measured spectrum at the resonant points. If the measured spectrum shown in Figure 3.8 or the adjusted spectrum shown in the last plot of Figure 3.11 is used in the first step of the algorithm, better results should be achieved. Table 4.2 shows the calculated and measured radiation using the measured current spectrum. To better illustrate the comparison, the estimated and measured radiation are plotted in Figure 4.1.

Table 4.1. Calculated and Measured Radiation Using Calculated Current Spectrum

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>190</th>
<th>530</th>
<th>890</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Amp)</td>
<td>0.005</td>
<td>0.001</td>
<td>0.0004</td>
</tr>
<tr>
<td>Impedance (ohm)</td>
<td>0.2</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>1.9</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Antenna factor (dB)</td>
<td>13</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Calculated radiation (dBm)</td>
<td>-54</td>
<td>-63</td>
<td>-74</td>
</tr>
<tr>
<td>Measured radiation (dBm)</td>
<td>-69</td>
<td>-78</td>
<td>-92</td>
</tr>
<tr>
<td>Difference (dBm)</td>
<td>15</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>
Table 4.2. Calculated and Measured Radiation Using Measured Current Spectrum

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>190</th>
<th>530</th>
<th>890</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Amp)</td>
<td>0.0014</td>
<td>0.00032</td>
<td>0.00011</td>
</tr>
<tr>
<td>Impedance (ohm)</td>
<td>0.2</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>1.9</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Antenna factor (dB)</td>
<td>13</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Calculated radiation (dBm)</td>
<td>-65</td>
<td>-73</td>
<td>-85</td>
</tr>
<tr>
<td>Measured radiation (dBm)</td>
<td>-69</td>
<td>-78</td>
<td>-92</td>
</tr>
<tr>
<td>Difference (dBm)</td>
<td>4</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 4.1. Comparison of Measured and Calculated Radiation
5. Other $|S_{11}|$ and Radiation $|S_{21}|$ Measurements

$|S_{11}|$ and radiation $|S_{21}|$ measurements were made on Boards 1, 2, and 7 to estimate the radiation efficiency and to evaluate a 3-layer board with an extra return plane. The experiments were made inside the shielded room as illustrated in Figure 5.1. A Wiltron 37247A network analyzer was used to make these measurements. The antenna can have a horizontal or vertical orientation. The test board can have up to six orientations. Figure 5.2 shows the test setup inside the shielded room, and Figure 5.3 shows the setup outside the shielded room. The test procedure is described in Appendix G in detail.

Figure 5.1. Test Setup for Measuring $|S_{11}|$ and Radiation $|S_{21}|$
Figure 5.2. Radiation $|S_{21}|$ being Measured Inside the Shielding Room

Figure 5.3. Test Setup Outside the Shielding Room

Figure 5.4 shows the measured $|S_{11}|$ and $|S_{21}|$ of Board 7, a two layer unpopulated board with the same dimensions as Board 6 as shown in Figure 1.2. The configuration for each plot is illustrated beside the plot.
Figure 5.4. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 7 at Corner Connector
Figure 5.5 shows similar experiments on a 3-layer version of Board 7. A 1-layer board of the same dimensions was added above Board 7 to form a 3-layer board. Layers 1, 3 were return planes and Layer 2 was the power plane. The two shorter edges of the return planes were connected by copper tape.
In addition, for the 3-layer Board 7, point connections were made between the two return layers instead of sealing two edges as shown in Figure 5.6. The connections were made using a strip of copper tape soldered to the two return planes. Experiments were made on boards with 4-point, 8-point, and 12-point connections, at corner or center connectors, and with two configurations. Figure 5.7 shows the experimental results.
$|S_{11}|$ of 3-Layer Board 7 Powered at Corner Connector

$|S_{21}|$ of 3-Layer Board 7 Powered at Corner Connector
\[ |S_{11}| \] of 3-Layer Board 7 Powered at Center Connector

\[ |S_{21}| \] of 3-Layer Board 7 Powered at Center Connector
\[ |S_{11}| \text{ of 3-Layer Board 7 Powered at Corner Connector} \]

\[ |S_{21}| \text{ of 3-Layer Board 7 Powered at Corner Connector} \]
Figure 5.7. $|S_{11}|$ or Radiation $|S_{21}|$ of 3-Layer Board 7 with Different Connections
The $|S_{11}|$ and radiation $|S_{21}|$ measurements were also made on Boards 1 and 2, the populated and unpopulated computer motherboard. The board was powered at location C2D5 in Region 1 or C6G3 in Region 2. Two configurations were oriented as illustrated by the small plot beside each figure. The experimental results are shown in Figure 5.8 for Board 1 and Figure 5.9 for Board 2.
Figure 5.8. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 1
Figure 5.9. $|S_{11}|$ and Radiation $|S_{21}|$ of Board 2
APPENDIX A

Test Procedure for Measuring Radiation Using Tektronix 2712 Spectrum Analyzer

The test procedure for measuring radiation from the power bus structures is described below. The words in **bold** face indicate a hard key on the front panel. The words in *italics* indicate a submenu in the display screen.

1. Turn on the analyzer.
2. Set up the spectrum analyzer:
   a). Set center frequency to 500 MHz: **FREQUENCY + 500 MHz**.
   
   Set frequency division to 100 MHz: **SPAN/DIV + 100 MHZ**.
   
   b). Set resolution bandwidth: press ↑ or ↓ in RES BW panel to set it to **300KHz**.
   
   c). Decrease VF: press **VID FLTR** in RES BW panel, the VF will be reduced to **3KHz**.
   
   d). Set vertical scale to 10 dB/div: press **10/5/1** as needed to set **10 dB/div**.
   
   e). Set the proper reference level: press ↑ near the **REF LEVEL** hard key several times until the reference value cannot be increased anymore.

   The settings are show on the display as:

   - **500MHZ**
   - **ATTN 0DB**
   - **-50.0DBM PRE**
   - **VF 3KHZ**
   - **100MHZ/ 10 DB/ 300KHZ RBW**

3. Set up the antenna and the test board:
   a). Use a long blue cable to connect the spectrum analyzer to Room Connector 1 that connecting the antenna terminals.
   
   b). Inside the shielding room, position the test board on the bench. Adjust the height and angle of the antenna to point to the board, record the antenna position.
   
   c). Remove everything unnecessary from the shielding room.

3. Measure the radiation from test board:
   a). Turn on the power switch of the board, close the door of the shielding room.
b). The radiation spectrum will show on the display screen. Press **MKR/Δ/OFF** once to activate a marker, use the knob or the **MKR ←** or **MKR →** to move the marker.

c). Use LabVIEW to record the data.

d). Change the orientation of the test board and the antenna, repeat measurement.

For more information on how to use Tektronix 2712 Spectrum Analyzer, refer to the user’s guide [1].
APPENDIX B
Test Procedure for Measuring Time-Domain Waveform Using Tektronix TDS 520A Digitizing Oscilloscope

The test procedure for measuring time-domain waveforms from the voltage/current connectors of the test board is described below. The words in **bold** face indicate a hard key on the front panel. The words in *italics* indicate a submenu in the display screen.

1. Turn on the oscilloscope.
2. Reset the oscilloscope: Press **SETUP**, press *Recall Factory Setup*, then **OK Confirm Factory init**.
3. Compensate the Tek P6139A test probe:
   a). Connect the probe to Channel 1. Connect the probe head to the SIGNAL and GND points in the PROBE COMPENSATION panel.
   b). Press **AUTOSET** to get a stable waveform.
   d). Use a 2.0m/m precision screwdriver to adjust the probe until you see a perfectly flat top square wave on the display. (See P3-110 of [5])
   e). Set the bandwidth back to *Full*.
4. Set up the oscilloscope:
   a). Press **VERTICAL MENU**, *Coupling DC*, then select AC. Toggle the Ω value to 1M.
5. Obtain the waveform from clock output:
   a). If measuring clock signal: Connect the ground clip of the test probe to the ground end of the battery, remove the cover of the probe tip, use the probe tip to touch the output pin of the oscillator.
   b). Press **AUTOSET**, then **RUN/STOP** to get a snapshot of the waveform.
   c). Use LabVIEW to record the data.
6. Obtain the waveforms from voltage/current connectors:

a). Attach a BNC-m to SMA-m connector to Channel 1, then connect the current/voltage connector of the test board directly to Channel 1.

b). Turn on the power switch of the board, press AUTOSET to get a waveform, adjust the horizontal or vertical scale as necessary using the scale knobs. Press RUN/STOP to get a snapshot. Turn off the power switch of the board. Measure the time or the voltage using cursor functions in the CURSOR menu.

c). Record the data.

For more information on how to use Tektronix TDS 520A Digitizing Oscilloscope, refer to the user’s guide [2].
APPENDIX C

Test Procedure for Measuring the Voltage/Current Spectrum Using Tektronix 2712 Spectrum Analyzer

The test procedure for measuring the voltage/current spectrum of the powered test board is described below. The words in **bold** face indicate a hard key on the front panel. The words in *italics* indicate a submenu in the display screen.

1. Turn on the analyzer.
2. Set up the spectrum analyzer:
   a). Set center frequency to 500 MHz: **FREQUENCY + 500 MHz**.
   
   Set frequency division to 100 MHz: **SPAN/DIV + 100 MHz**.
   
   b). Set resolution bandwidth: press ↑ or ↓ in RES BW panel to set it to **300KHz RBW**.
   
   c). Decrease VF: press **VID FLTR** in RES BW panel, the VF will be reduced to **3KHz**.
   
   d). Set attenuation: press **INPUT** in MENUS panel, press 5 to select **RF ATTENUATION**, then enter **30 + dBx** to set attenuation to 30 dB.
   
   e). Set vertical scale to 10 dB/div: press **10/5/1** as needed to set **10 dB/div**.
   
   f). Set the proper reference level: press ↑ near the **REF LEVEL** hard key several times until the reference value cannot be increased anymore.

   The settings are shown on the display as:
   
   500MHZ ATTN 30DB
   
   -20.0DBM PRE VF 3KHZ
   
   100MHZ/ 10 DB/
   
   300KHZ RBW

3. Measure the test board:

   a). Make sure a DC block with a SMA connector is installed to the RF input. Connect the test board by the current connector or one voltage connector.
b). Turn on the power switch of the board, the spectrum will show on the screen. Press **MKR/A/OFF** once to activate a marker, use the knob or the **MKR ←** or **MKR →** to move the marker from peak to peak.

c). Use LabVIEW to record the data.

For more information on how to use Tektronix 2712 Spectrum Analyzer, refer to the user’s guide [1].
APPENDIX D

Test Procedure for Measuring Input Impedance Using HP4291A HF Impedance/Material Analyzer

The test procedure for measuring input impedance of the power bus structures is described below. The words in bold face indicate a hard key on the front panel. The words in italics indicate a submenu in the display screen.

1. Turn on the analyzer, warm up 30 minutes.

2. Calibration:
   a). Settings: Press Format, select SMITH CHART. Press Meas, select REFLECTED COEFFICIENT. Press Sweep, then NUMBER OF POINTS, use ↑ and ↓ to set it to 1601 points.
   Press Cal, then CALIBRATE MENU.
   b). Turn the connector on the high impedance test head until the connector sleeve is fully extended. Connect the open termination by fixing the center conductor and turning only the shield. Press OPEN, wait until hearing the beep. Do the same with the short, 50 Ω, and low-loss capacitor terminations. After calibration, press DONE: CAL. A "CO+" notation will appear in the left side of the display.

3. Port Extension:
   a). Attach a 7mm to 3.5mm-f precision adapter to the test head, then connect a precision microwave cable to the adapter. Next, connect an open or short probe same as the one used on the test board.
   b). Press PORT EXTENSION in the Cal menu, press EXTENSION to toggle it on. Then press EXTENSION VALUE. Use the knob or enter propagation delay (several ns) to adjust the extension length until the line in the Smith chart turns into a dot in open or short positions. Press RETURN. A “Del” notation will appear in the left side of the display.
4. Fixture compensation:

With the open probe attached to the end of the cable, press \textit{FIXTURE COMPEN}, then \textit{COMPEN MENU}, press \textit{OPEN}. Do the same to the short probe. Press \textit{DONE:COMPEN}. A “CMP” notation will appear in the left side of the display.

5. Set up the analyzer:

a). Connect the test board.

b). Set up the analyzer:

Press \textbf{Start} + 1 M/\mu to set the start frequency to 1 MHz.

Press \textbf{Stop} + 1 G/n to set the stop frequency to 1 GHz.

Press \textbf{Meas} + Ch1, select \textit{IMPEDANCE: MAG(|Z|)}.

Press \textbf{Meas} + Ch2, select \textit{PHASE(\Theta_z)}.

Press \textbf{Format} + Ch1, select \textit{LIN Y-AXIS}.

Press \textbf{Format} + Ch2, select \textit{LIN Y-AXIS}.

Press \textbf{Display}, select \textit{DUAL CHAN ON} and \textit{SPLIT DISP ON}.

The display will split into two plots, corresponding to impedance magnitude and impedance phase.

6. Measure the board:

a). Press \textbf{Scale/Ref} then \textit{AUTO SCALE} for both channels to get a good display.

Press \textbf{Marker} for a marker, use the knob to move the marker.

b). Obtain an equivalent circuit: Press \textbf{Display}, then \textit{EQUIV CKT MENU}, then \textit{SELECT EQU CKT}, select an appropriate model then press \textit{CALCULATE EQU PARAMS}, the parameter values will appear on the display.

c). Record the data using LabVIEW.

For more information on how to use HP4291A HF Impedance/Material Analyzer, refer to the user’s guide [3].
APPENDIX E
Matlab Program to Calculate Board Impedance and Effective Capacitance from Measured Voltage/Current Spectrum

% Program to calculate board impedance and effective capacitance of power bus
% for test board #6 with 1 MHz oscillator

clear all; clf;

% Input current filename
fname=input('Enter the filename as string:');

% Load file
eval(['load ',fname]);

% Obtain the current spectrum and plot the result
eval(['f=' fname '(:,1);']);
eval(['iamp=' fname '(:,2);']);
subplot(221)
plot(f,iamp);
axis([0 1e8 -80 -20]);
ylabel('Amplitude in dBm')
title('Current spectrum for test board #6, 1M osc')
zoom on
grid on

% Obtain the peaks at each harmonics
k = 1;
for m = 1:511
    if abs(f(m)-k*1e6) < 1e5
        bottom = max(1, m-2);
top = min(m+2, 511);
[I(k) I_index(k)] = max(iamp(bottom:top));
I_index(k) = f(I_index(k)+bottom-1);
k = k+1;
end
end

% Plot the peaks on each harmonics
hold on
plot(I_index, I, 'ro');
hold off

% Input voltage filename
fname=input('Enter the filename as string:');

% Load file
eval(['load ',fname]);

% Obtain the voltage spectrum and plot the result
eval(['f=' fname '(:,1);']);
eval(['vamp=' fname '(:,2);']);
subplot(222)
plot(f,vamp);
axis([0 1e8 -80 -20]);
ylabel('Amplitude in dBm')
title('Voltage spectrum for test board #6, 1M osc')
zoom on
grid on
% Obtain the peaks at each harmonics
k = 1;
for m = 1:511
    if abs(f(m)-k*1e6) < 1e5
        bottom = max(1, m-2);
        top = min(m+2, 511);
        [V(k) V_index(k)] = max(vamp(bottom:top));
        V_index(k) = f(V_index(k)+bottom-1);
        k = k+1;
    end
end

% Plot the peaks at each harmonics
hold on
plot(V_index, V, 'ro');
hold off

% Calculate board impedance
Z_index = I_index;
Z = 3.3 .* (10.^(V-I)/20);
subplot(223)
stem(Z_index, Z);
axis([0 1e8 0 4])
xlabel('Frequency in Hz')
ylabel('Impedance in ohm')
title('Impedance')
zoom on
grid on
% Calculate effective capacitance
C_index = L_index;
C = 1e9./(2*pi.*C_index.*Z);
subplot(224)
stem(C_index, C);
axis([0 1e8 0 50])
xlabel('Frequency in Hz')
ylabel('Capacitance in nF')
title('Effective capacitance')
zoom on
grid on
APPENDIX F
Test Procedure for Measuring S Parameters Using HP8753D Network Analyzer

The test procedure for measuring the input impedance of the power bus structures is described below. The words in **bold** face indicate a button on the front panel, the words in *italics* indicate a submenu on the display screen.

1. Turn on the network analyzer, warm up 45 minutes.
2. Connect two precision cables to Ports 1 and 2.
3. Set up measurements: (This step must be done before calibration, since the settings cannot be changed after calibration.)
   a). Set frequency range: Press **START**, then press **1+M/μ** to set the start frequency to 1 MHz. Press **STOP** and **3+G/μ** to set the stop frequency to 3 GHz.
   b). Set the number of sampling points: Press **MENU**, select **NUMBER OF POINTS** in the submenu, then use the up arrow button below the knob to increase this number to 1601 points.
   c). Reduce the IF bandwidth to get a stable curve: Press **AVG**, select **IF BW** in the submenu, then use the down arrow button below the knob to decrease the bandwidth to 1000 Hz.
4. Calibration:
   a). Change the model of calibration kit: Press **CAL**, then press **CAL KIT[7mm]** in the submenu, select **3.5mmD** as the model of the calibration kit. ("7mm" is the default model.) Press **RETURN**.
   b). Set calibration type: Press **CALIBRATE MENU**, then select **FULL 2-PORT** submenu, since \(S_{11}, S_{22},\) and \(S_{21}\) will all be measured.
   c). Calibrate: Press **REFLECTION**, connect the open termination to Port 1 and press **OPEN** in the **FORWARD** panel in the display. Do the same with the short and matched load terminations to Port 1. Disconnect the standards from Port 1 and connect it to Port 2. Do the same to calibrate Port 2. After calibration, press **STANDARDS DONE**.

Use an f-f connector to connect the two cables to form a through connection. Press **TRANSMISSION**, then press all its submenus in turn.

Press **ISOLATION**, then **OMIT ISOLATION**, then **ISOLATION DONE**.
Complete calibration: press **DONE 2-PORT CAL**. A "Cor" sign will appear at the left side of the screen.

d). Save the calibration: Press **SAVE/RECALL**, choose the first submenu **SAVE STATE** to save the settings and calibrations to the internal memory of the network analyzer.

5. Port extension:

a). Extend Port 1: Press **MEAS**, select **Refl: FWD S11 (A/R)**. Press **FORMAT**, then select **SMITH CHART**. Connect to Port 1 an open or short probe that has the same length as the probe used in DUT. Press **CAL**, select **MORE** in the submenu, then select **PORT EXTENSIONS**. Next, press **EXTENSIONS** submenu on the top to turn the extension on, then press **EXTENSION PORT 1**. Use the knob to increase the delay until the line in the Smith chart turn into a dot in the open or short position. Press **RETURN**, a "Del" sign will appear in the left side of the screen.

b). Extend Port 2: Press **MEAS**, select **Refl: REV S22 (B/R)**. Press **FORMAT**, then select **SMITH CHART**. Connect to Port 2 the same probe, press **CAL**, select **MORE** in the submenu, then select **PORT EXTENSIONS**. Next, press **EXTENSION PORT 2**. Use the knob to adjust the delay as before.

6. Display the results:

a). Remove the probe from the cable, connect the test board.

b). Press **FORMAT**, select **LOG MAG**. Press **MEASURE**, select **Refl: FWD S11 (A/R)** to measure $|S_{11}|$, or select **Trans: FWD S21(B/R)** to measure $|S_{21}|$, or select **Refl: REV S22(B/R)** to measure $|S_{22}|$.

c). Press **SCALE REF** then **AUTO SCALE** to get a good display.

d). Use LabVIEW® to record data.

For more information on how to use the HP8753D network analyzer, refer to the user’s guide [4].
APPENDIX G

Test Procedure for Measuring Radiation $|S_{21}|$ Using Wiltron 37247A Network Analyzer

The test procedure for measuring the radiation $|S_{21}|$ of a test board is described below. The words in **bold** face indicate a hard key on the front panel. The words in *italics* indicate a submenu in the display screen.

1. Turn on the network analyzer and warm up 1 hour.
2. Connect Port 1 (power) of the network analyzer to Room Connector 1 and Port 2 (receiver) to Room Connector 2.
3. Calibrate the network analyzer (follow the procedures show in the display):
   a). Press **Begin Cal**, use the □ or ● buttons to select NEXT CAL STEP. Press **Enter**. Then, select FULL 12-TERM in the next menu, press **Enter**. Select EXCLUDE ISOLATION. Select NORMAL 1601 POINTS MAXIMUM, press **Enter**. Adjust start and stop frequencies as necessary. Select 1601 MAX PTS, press **Enter**. Select NEXT CAL STEP, press **Enter**. Set PORT 1 CONN and PORT 2 CONN to GPC-3.5(m). Set LOAD TYPE to BROADBAND. Set TEST SIGNALS to 0.00dB. Press START CAL.
   b). Connect the two matched load terminals to ports, press **Enter**, wait till the measurements done.
   c). Connect an open terminal to Port 1 and a short terminal to Port 2. Press **Enter**.
   d). Connect a short to Port 1 and an open to Port 2. Press **Enter**.
   e). Disconnect both terminals, make a through line connection to Port 1 and Port 2. Press **Enter**.
   f). Press **Save/Recall Menu** then SAVE, press **Enter**. Select FRONT PANEL SETUP AND CAL DATA ON HARD DISK, then CREATE NEW FILE, use keyboard to enter the file name.
4. Test setup: Position the test board on the bench, connect one probe to Room Connector 1 and then Port 1 of the network analyzer to bring in power. Connect the antenna terminals to Room Connector 2 then Port 2 of the network analyzer. Adjust the height, distance and angle of the antenna. Record antenna position.
5. Measure and record the data:
   a). Turn on the power switch of the board, close the door of shielding room.
       Press Channel Menu, select DUAL CHANNELS 1 & 3.
       Press Auto Scale.
   c). Insert a floppy disk to the disk drive. Press Menu in the Hard Copy panel.
       Select DISK OPERATIONS, then TABULATE DATA TO FLOPPY DISK. Use the
       keyboard to enter a new file name, record data.
   d). Data should be processed using a C program.

For more information on how to use the Wiltron 37247A Network Analyzer, refer to the
user’s guide [5].
REFERENCES


